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Scott Wood  
*University of Notre Dame Australia*

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# Development of a system to Optimise Water Recharge and Timber Production from *Pinus pinaster* Aiton Plantations on the Gnangara Water Mound

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Research Thesis submitted to the University Notre Dame, Australia for Doctor of Natural Resource Management

By Scott Wood

Supervising Professors

Dr Syd Shea University of Notre Dame  
Dr Louis Caccetta Curtin University

24 April 2011

## Declaration:

*This research thesis is all my own work, except where duly acknowledged. Words or passages taken from other sources are marked with quotation marks and appropriate references.*

**Signed:** \_\_\_\_\_ **Date:** 28/4/2011

# ABSTRACT

In 1996, the Western Australian Government decided to progressively liquidate 21,000 hectares of *Pinus pinaster* Aiton plantations located 20 kilometres north of Perth on the Gnangara Water Mound. The decision was made for a number of reasons but one of the principal concerns was the conflict between water use and timber production. The decision to liquidate the plantation over a prescribed period while meeting a legal requirement to produce timber for a laminated veneer lumber plant provided the opportunity to integrate the large database on plantation growth and water recharge and use operational research models to determine the optimum liquidation scenario.

*Pinus pinaster* Aiton growth on the Gnangara Water Mound on sites with shallow water tables was found to be less than on sites with deep water tables. This indicates that the trees on these shallow sites, with depths to water table of five to ten metres, are not accessing the water table. Consequently, it is concluded that it is the volume of the water in the unsaturated zone, beneath the trees that is the factor limiting growth not the depth of the water table.

Leaf area index (LAI) can be derived from satellite photography except in stands with very open canopies. The relationship between LAI and the extent to which groundwater is recharged is critical. The relationship between Leaf Area Index and Basal Area was not linear as has been assumed in previous recharge models but there was a strong relationship between tree growth and Leaf Area Index. LAI is subject to a number of influences which include amongst other species, age and stand density.

Site maximum LAI for *Pinus pinaster* Aiton was 3.3 on the Gnangara Mound.

Leaf Area Index regrowth for *Pinus pinaster* Aiton on the Gnangara Mound after thinning for a whole stand could be explained by:

$$\text{LAI regrowth} = z_0 + a(\text{SPH}) + b(\text{AGE}) + c(\text{SPH} * \text{SPH}) + d(\text{AGE} * \text{AGE})$$

(where SPH is stems per hectare and AGE is time since planting).

The LAI growth curve of unthinned young (<20 years old) stands was sigmoidal and explained by  $\text{LAI} = 3 / (1 - 81^{((3.5 + 12 / 2\text{-year}) / 12)})$ .

This pattern is probably caused by increasing reductions of water availability. Because of this LAI pattern for young stands (<20 years old) it was hypothesized that the water recharge /age relationship for these stands is a negative sigmoid. That is it inversely mirrors the growth rates of LAI. Consequently the proportion of total rainfall used by plantations would increase with increasing LAI until it reaches the site maximum LAI and then plateaus. Combining the recharge relationship with LAI growth for the same ages of young stands (below 20 years of age) results in a negative linear relationship where  $\text{percentage recharge} = -15 * \text{LAI} + 45$ .

This differs for the LAI to recharge relationship used in PRAMS( Perth Regional Aquifer Model) which proposes that above LAI 1.5 there is a complete extinguishment of recharge.

The hypothesised negative linear relationship of LAI to water recharge is more readily able to explain the LAI to age pattern for young stands(<20 years old) whereas a full extinguishment at LAI 1.5 is not able to explain the ongoing LAI growth to 3.3. It is not conceivable that a plant would double its transpiration and rainfall interception area if it has already reached the limitation of full site water usage as proposed in PRAMS. There will always be some uncertainty in the LAI to water recharge relationship because it is impossible to measure directly. Sensitivity analysis was used to accommodate any departure from the actual relationship. LAI does have a strong inverse relation to water recharge. Consequently, LAI minimization within a model would have the same effect as maximizing the water recharge.

A Gngangara Mound Model was developed to provide a high level decision support tool that could effectively evaluate the relationship between water recharge and timber production. The model required a number of scenarios to test sensitivity to growth rates, recovery percentage

of Laminated Veneer Lumber (LVL) from gross volumes, increasing volume requirements and shorter liquidation periods. Changing the objective to one of minimizing LAI (equivalent to maximizing ground water recharge) was tested to determine if it would give a significantly different result to that obtained with a maximize volume objective.

The effect of a number of harvesting regimes and other management options on the change in average per annum water recharge derived from the Gngangara Mound Model are listed below:-

- Increasing the frequency of prescribed burning native vegetation, increased recharge by 33.5 GL/yr.
- A reduction of private and public abstraction from 370 to 304GL/yr, increased recharge by 66 GL/yr.
- Harvesting regime for Sustainable timber volume supply to 2026, increased recharge by 45.5 to 55 GL/yr.
- Harvesting regime for Minimize LAI with 100000 m<sup>3</sup> minimum annual timber volume until 2026, increased recharge by 47.6 to 58.2 GL/yr.
- Harvesting regime for Sustainable timber volume supply to 2016, increased recharge by 50.5 to 62 GL/yr.

An equal area of Banksia, at LAI 1, to the pine plantations would recharge annually 39.4 to 36.2 GL. A continuing lower rainfall of 100mm less than long term average would mean a reduction of recharge annually of 107 GL to that achieved prior to 1970.

Within the constraints of the State Agreement Act a small increase in water recharge could be achieved by using a harvesting schedule with an objective that minimizes LAI provided the volumes from 2008 to 2026 are no lower than 117000 m<sup>3</sup> per annum.

It is also possible to combine this scenario with maximizing the liquidation of Gngangara plantation rather than the Pinjar and Yanchep plantations within the next 5 years. The combination of these two scenarios would result in the best water outcome (3.2 GL per annum) within the timber production constraints of achieving a minimum of 117000m3 per annum.

Early liquidation of the plantation will increase the water recharge but the water outcomes are small (5-7 GL per annum) in comparison to the timber volume loss and potentially could result in significant costs. Far greater savings could be achieved at a lower cost by using other management strategies such as reduction in *Banksia* water use through prescribed burning or less water extraction for private use. Small gains in water production would be lost by only a small reduction in annual rainfall due to continuing climate variability.



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# 1. Introduction

## i) Background and outline of the study

The Western Australian Government on the advice of the Department of Conservation and Land Management (CALM) decided in 1996 to progressively liquidate the 21,500 hectares of *Pinus pinaster* Aiton plantation resource 20 kilometres north of Perth, which had been established over the previous 80 years. The plantations are located on the Gnangara Water Mound, which currently provides 40% of the water consumed in the Perth region (Figure 1).

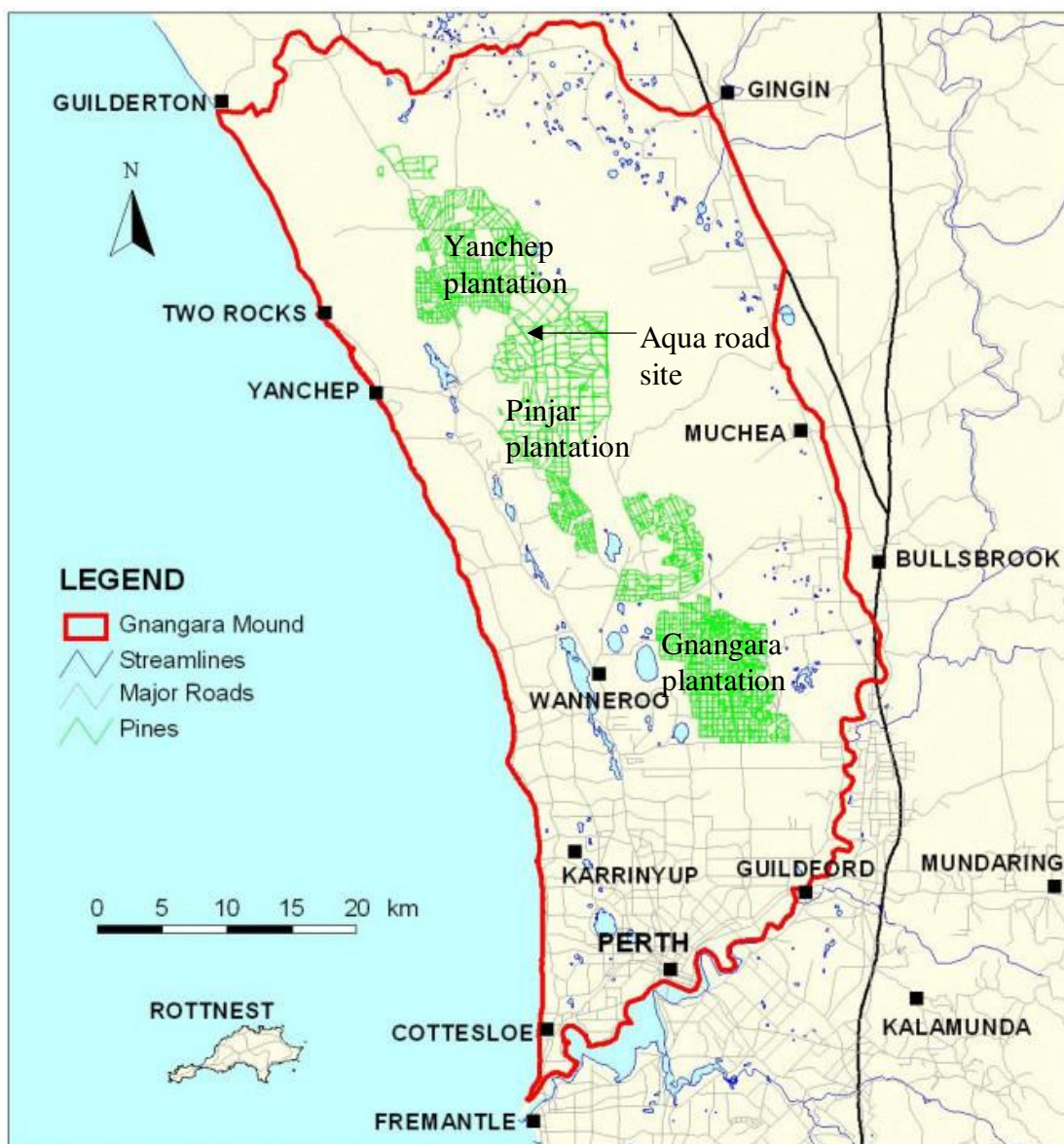


Figure1. The location of the *P. pinaster* Aiton plantations in relation to the Gnangara Water Mound

The area of plantations of *Pinus pinaster* Aiton on the Gnangara mound is made up of three recognised plantations; Gnangara, Pinjar and Yanchep plantations (Figure 1).

The decision to liquidate the stands and cease replanting was brought about by a number of factors including the perceived increasing conflict between timber and water production on the Gnangara Water Mound, the increasing incidence of wildfires resulting from arson and the demonstrated capacity to grow *P. pinaster* Aiton more efficiently on cleared agricultural land at other locations.(Shea.S.R. Pers Com.) It is expected the harvesting of all of the plantations will be completed between 2004 and 2029.

The existence of the plantations on the Gnangara Water Mound became a concern from the mid 1970s because of increasing awareness of the conflict between extraction of water for domestic use, the extraction of water by the pine plantations and projected shortages of water to Perth consumers because of drought. The increase in water use from the Gnangara Mound for domestic consumption also resulted in conflicts with conservation values. Rare and endangered subterranean species that occur in the Yanchep cave system are thought to be dependant on the maintenance of groundwater levels for their survival (Wilkens, H., Culver, D. C. & Humphreys, W.F. 2000).

The plantation silvicultural systems were progressively modified from the mid 1970s in an attempt to ameliorate these conflicts (Butcher 1979). The basal area was reduced to attempt to achieve a rotational average of 11m<sup>2</sup> basal area. The future land use of the Gnangara Mound has become a major planning issue for the Western Australian State Government involving several different State Government Agencies. The Gnangara Sustainability strategy 2009 has recently been published (Department of Water 2009)

The decision to liquidate the plantations has also enabled the Government to allocate 160,000 cubic metres of logs per annum over a 25-year period to Wesbeam Pty Ltd for the production of Laminated Veneer Lumber (LVL). This was possible because it was previously seen as an under utilised resource (Professor Dr Syd Shea 2008, Notre Dame University Fremantle former Executive Director CALM pers. comm.). This resulted in 2004 in the construction of a factory producing LVL with a work force of approximately 140 people. It was necessary for the Western Australian Government to legislate an Agreement Act in order to secure the investment required. The government passed legislation (*Wood Processing (Wesbeam) Agreement Act 2002*) which has provided an opportunity to utilize the pine resource for a high value product but it has also constrained the rate and method by which the plantations can be liquidated.

The requirements to meet both the log resource contracts and maximise water recharge to a significant groundwater resource provide a unique opportunity to scientifically evaluate the impact of significantly different harvesting regimes on the costs and benefits to water, timber production, conservation assets and potentially other land uses. To accomplish this, an integration of the large amount of forest growth and hydrological data and the utilisation of operational research methods to develop temporal and spatial harvesting regimes, which would optimise the water, timber and conservation resources of the area was required.

Normal pine plantation management in Western Australia is aimed at optimising wood production. It involves establishment, two to four thinning operations, clear falling and replanting over a 30 to 40 year cycle. This normal harvesting schedule does not necessarily allow for optimisation of land use for other values like water recharge. To achieve a greater water recharge outcome significant departures from normal harvesting schedules may be required.

Previously the Forest Products Commission (which succeeded CALM and is now the State Government Agency responsible for forest management in Western Australia) has concentrated on evaluating a limited number of harvesting scenarios, which involve maximising the wood production. Theoretically, if wood fibre production was the only consideration, the optimum harvesting regime would involve the retention of trees throughout the total area for as long as possible at densities that optimised wood production. Even a harvesting regime that maximised wood fibre production would not necessarily be the optimum regime for the production of logs to be utilized for laminated veneer lumber. In addition to timber production the government is seeking to balance the water usage from the area to meet both the demand for water for the metropolitan area and that required for conservation habitat in the Gnangara region.

The need to seek increased water production from any potential source has been driven in part by an apparent change in climate. Average annual rainfall since 1969 has been reduced by approximately 100 mm per annum to an average of 720mm between 1969 and 2007 at Wanneroo compared to average rainfall of 820mm over the period from 1914 to 1968 (Water Corporation 2008).

## **ii) Need for and significance of the study**

This study is essential to determine if it is possible to vary the rate and method of harvesting the plantation to increase water yield while at least maintaining timber yield at levels that meet the legal obligations of the State Government to supply timber of specified dimensions to the Laminated Veneer Lumber Plant. This plant commenced operations in 2004 and has legal rights to 4 million cubic metres of timber up to the year 2029.



The techniques, which have been developed, should also have direct relevance for the new Maritime Pine plantings occurring in the lower rainfall zone of Western Australia. These are located on cleared agricultural land and the objective of these plantings is to increase water consumption in order to minimise salinity and water logging. Measurement techniques for leaf area available to this study and a thorough understanding of leaf area dynamics and its relationship to water use and growth developed in this thesis are likely to be the most transferable aspect of the research which has been undertaken in this study.

The overall objective of this thesis was to investigate and compare the options that are available to optimise the yield of water (ceasing or reducing the decline of groundwater levels) and timber by analysing the effect of different pine harvesting regimes on the principal products derived from the area - water and timber. A conceptual approach to the study is illustrated in Figure 2.

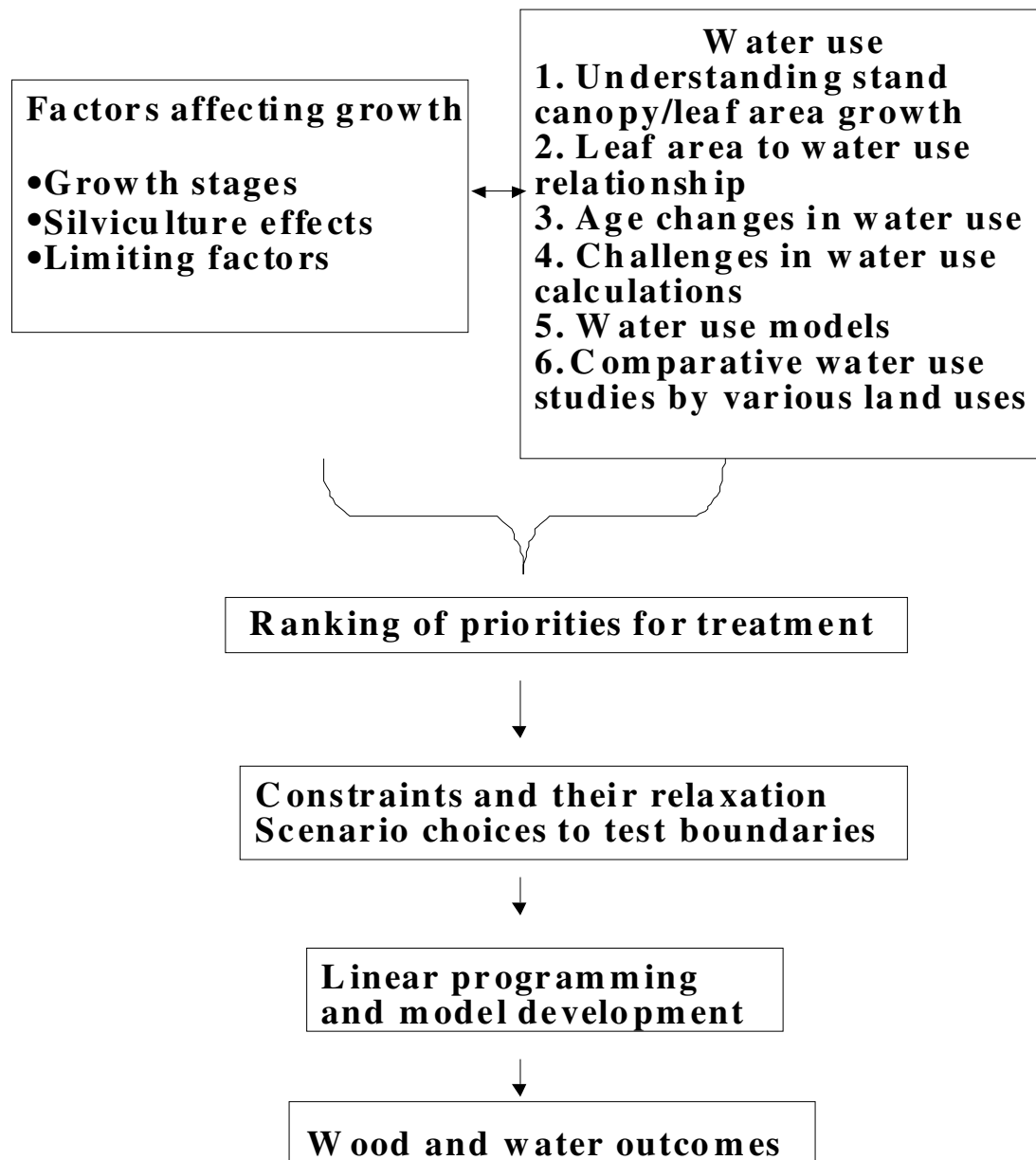


Figure 2. Conceptual approach to the study

Specifically the thesis provides for:–

1. A synthesis of the large amount of data on factors affecting growth and development of *P. pinaster* Aiton and the relationship between leaf area and groundwater recharge.
2. The provision, to managers, of a range of options for harvesting the plantation resource with a comparative assessment of each regime on timber production and groundwater recharge.

### iii) Issues being analysed and investigated in the study

The overarching research questions for this study were: -

- What is the optimum harvesting regime that provides the best water recharge outcome within the timber volume constraints that apply because of contractual commitments that are supported by legislation?
- Whether and how much additional groundwater recharge can be achieved by the progressive relaxation of the volume constraints and the manipulation of the timing and spatial harvesting strategies?

The following specific Modelling and Scheduling Questions were addressed -

- The *Wood Processing (Wesbeam) Agreement Act* (2002) contains constraints, which limit the options of what stands can be removed over the period of the contract. However, it may be necessary to depart from the contract schedule to achieve a larger water outcome. Before this can be considered, an evaluation of what the impacts of a relaxation of those constraints on water yield and timber outcomes is required.
- What series of scenarios can be used to test and compare different wood outcomes and their impact on water availability?
- Which scenario gives the best water outcome?

Other factors affecting the Gngangara Mound ground water system need to be understood so that sensible recommendations can be made. For example, are pruning, burning of litter and native bush prescribed burning significant factors affecting ground water recharge?

An attempt has been made to qualify and quantify the effect of these factors on ground water recharge. However, the time frames and expertise required in making specific recommendations were beyond the scope of this thesis. Some attempt, however, has been

made to make general recommendations on these external, but relevant, issues to allow the effect of harvesting regime options to be placed in the context of other management options.

There were a number of detailed factors that needed to be evaluated to achieve the objectives of this study.-

- The impact of different spatial and temporal harvesting regimes on groundwater recharge in different locations on the Gnamangara Water Mound.
- A general understanding of the water inputs and outputs of the Gnamangara Mound and how all land use changes have impacted upon this.
- The future climate regime. There has been a decline of rainfall since 1969. The period between 1914 and 1968 is recognized as much wetter than the period from 1969 and 2007.

The total cumulative reduction of rainfall is 3 metres since 1969 (on average approximately 100 mm less per year) at Wanneroo when this period is compared to the average rainfall that had occurred between 1914 and 1968. (Figure 3)

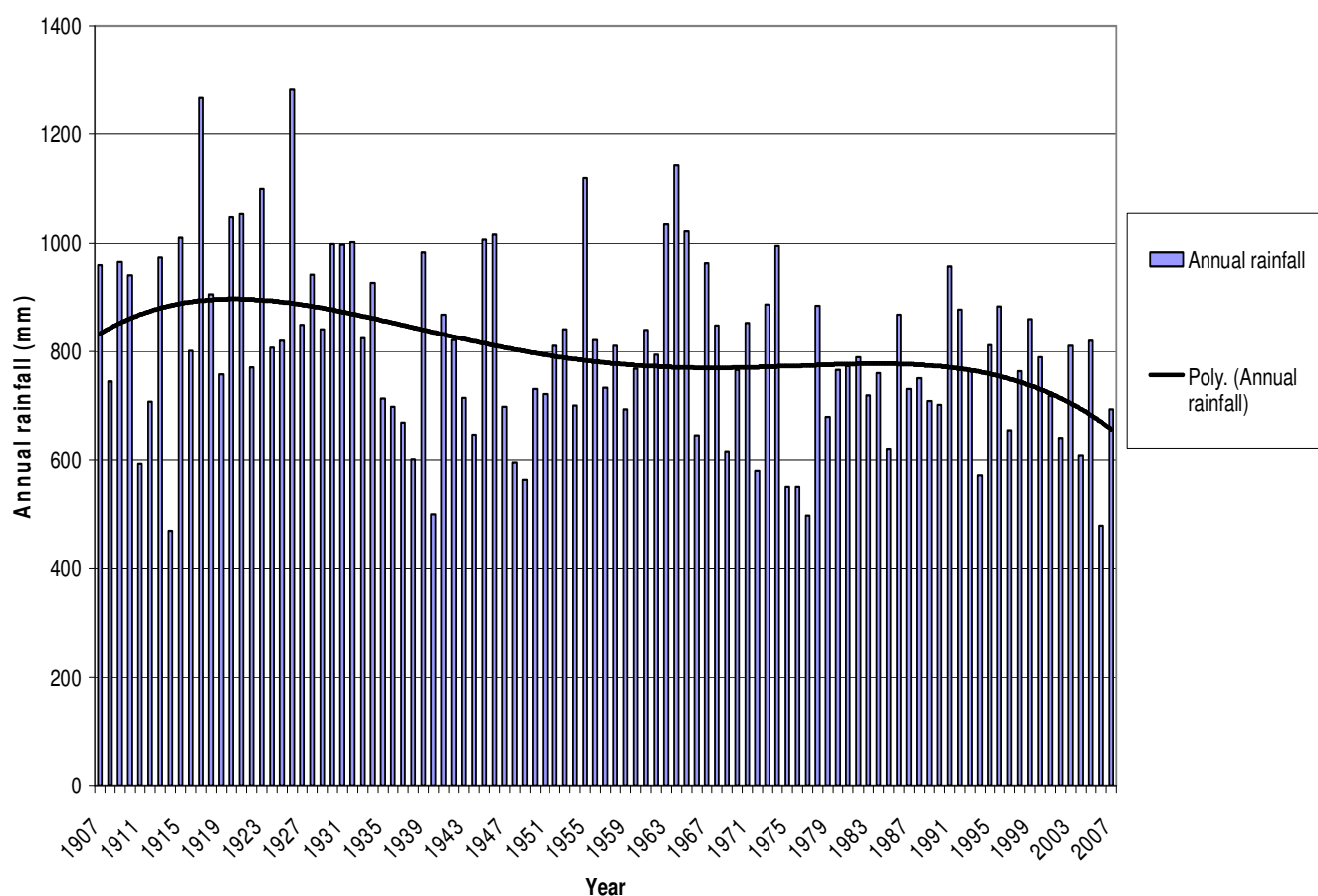


Figure 3. Annual Rainfall Perth from 1907 to 2007, Source Bureau of Meteorology

The decline in rainfall emphasizes the need to recognise that there are other factors, in addition to the pine plantation on Gnangara Mound, that have contributed to the decline in groundwater levels. For example, “The decline in water tables has occurred over a very long time period, and that during this time, both private and public use has increased very substantially” (Peer Review Group 2002 p.2) and “that the current groundwater levels are the consequence of a combination of factors, which include climate, abstraction and land use, over a long period of time” (Response to Peer Review Panel Comments 2002 p. 2). This confirms that it would be incorrect to attribute the decrease in groundwater levels to a single factor alone.

## 2. Leaf Area Index

### i) What is it and is it important?

Leaf Area Index (LAI) is the one-sided leaf surface area per unit of land surface (N.J.J. Breda 2008). It is measured as  $\text{m}^2$  of leaf area per  $\text{m}^2$  of land surface. McVicar et. al. (1996) claims that LAI is an important parameter in controlling water balance of a given vegetation type. The leaves regulate the exchange of water, carbon and oxygen. LAI describes a key property of the plant's canopy in its interaction with the atmosphere; especially with regard to radiation, energy and gas exchange (Monteith and Unsworth 1990). Whitehead (2003) states, "estimation of leaf area index is crucial for interpreting the contribution of trees and forest floor vegetation to carbon and the water balance" (p. 91). Dong et. al. (2001) also recognise it as a very important physiological characteristic that strongly influences plant water use and dry matter production. Asner et al. (2003) view canopy leaf area as the dominant factor controlling photosynthesis, transpiration and energy exchange. Hence, canopy leaf area is often treated as a core component of field and modelling studies. Many models have been developed which are sensitive to and driven by LAI estimates (Hall et al. 2003).

### ii) Measuring LAI

Pontailleur et al. (2003) contend that allometric relationships can be used to predict plant leaf area from plant stem measurements such as diameter. However, considerable time and effort may be required to establish robust and accurate relationships from representative samples. One difficulty is that these relationships, determined on plants at a given phenological state or in a given season, may only be appropriate for the times during which they were generated. For example, the relationship between basal area and LAI may be strongly linear during a particular period of tree growth but over the whole life of the tree this simple relationship may not apply (Samson et al. 1998).

The existing methods for quantifying LAI by direct measures via destructive harvesting techniques although accurate for the sample taken are prohibitively labour-intensive. The inability to take a large sample by destructive harvesting may not give any better result than a calibrated satellite photo. Satellite-based remote sensing observations are rapid and appropriate for a wide range of measurement scales provided they are calibrated by destructive harvest sampling (Chen et al. 2003).

The history of use of satellite remote sensing began in 1972 when the first civilian Satellite Remote Sensor Landsat one was launched (Samant and Kumar 2005). Landsat's primary objective was the mapping and monitoring of land cover. Use of remote sensing for estimating LAI of forests according to Ustin et al. (1993) was common by 1993.

Satellite remote sensing data have been used to estimate LAI based on relationships between it and LAI measurements obtained from the field (Hall et. al. 2003). Skidmore et. al. (1997) report that LAI values have been correlated with the visible, near infrared and middle-infrared bands from remote sensing. LAI has a consistent negative correlation with red reflectance in remote sensing. The Normalized Difference Vegetation Index (*NDVI*) is used to measure vegetation cover from multispectral satellite data. Nemani and Running (1989) concluded however, that *NDVI* cannot be used to estimate LAI for very open canopy conditions. Consequently, satellite derived LAI may produce inaccurate results for stands with very low stockings, which would have a very open canopy.

Hall et. al. (2003) state that :-

“Variability in LAI results occurs depending on how and where the destructive sampling of individual trees for a given species is carried out, such as sampling a representative range of tree sizes (p. 412). As a result, even absolute measurements of LAI for remote sensing

validation are challenged and sometimes compromised by issues of spatial scale, positional accuracy, and field sampling intensity” (p. 413).

Rautiainen et. al. (2003) state that “reflectance models are not yet common” and that is important to account for reflectance from soil, understorey and stand structure (p. 315). When the under-storey has a lower reflectance than the tree layer for instance, or there is a large proportion of bare soil below the canopy that can be detected from aerial observations, then a decrease in overall stand reflectance is observed as a function of LAI. When the under-storey has a higher reflectance than the tree layer for example, in boreal forests and where soil is rarely exposed, the opposite is observed.

### **iii) LAI growth**

Dean and Baldwin (1996) propose that: -

- During the course of stand development, leaf-area index peaks and either remains constant or declines slightly with age.
- Different species on different site qualities have different maximum LAI. Even the same species on different sites can have different maximum LAI
- A stand fully occupies a site when it has amassed the maximum LAI that a site can support.
- “To support LAI at its maximum, stands with only a few trees need much more wood than stands with greater numbers of trees” (Dean and Baldwin 1996 p. 149).
- The slope relationship between average stand diameter and trees per unit area also indicates that more basal area is required to support maximum levels of leaf-area index as trees per unit area declines.
- Physical limitations of tree stems do not allow a stand to maintain maximum LAI throughout its development, causing leaf-area index to decline.



Mason (2000) found that the interception of radiation increased with increasing amounts of foliage, at least up to a LAI of  $3.5 \text{ m}^2/\text{m}^2$  in New Zealand for *Pinus radiata* D.Don. Mason (2000) points to the findings of Madgwick, Jackson and Knight (1977) that the foliage mass of *P. radiata* D.Don increased with age until an equilibrium level was reached. Mason (2000) also states that the same results were found, for Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, in Long and Smith (1984) found the rate of approach to the maximum was greater at higher stockings. Mason (2000) suggests that it appears that “foliage mass was independent of density at stockings greater than 400 stems/ha, but diminished with diminishing stocking below this level” (p. 1).

Battaglia et. al. (1998) state “in eucalypt plantations, LAI increases as stands develop and then tends to stabilize or decline only slightly, effectively achieving a steady state or equilibrium” (p. 521).

Sampson et al. (1998) found that the Loblolly pine (*Pinus taeda* L.) basal area to LAI relationship is strongly linear in the early stages of tree development but the relationship decouples becoming asymptomatic as the stands grow. Sampson et al. (1998) suggest this could be because as heartwood is laid down the sapwood to basal area ratio decreases, resulting in a reduction in resource supply or a reduction in basal area growth per unit LAI. It appears that there is only a strong linear relationship between sapwood and LAI.

Medhurst and Beadle (2001) found for *Eucalyptus nitens* H.Deane & Maiden, that LAI increased at a constant rate soon after thinning regardless of residual stand density and this was correlated with changes in crown length. However, leaf area increase per tree was strongly influenced by residual stand density in the long term.

Dean and Baldwin (1996) conclude that although growth is only one of many physiological processes, intercepted radiant energy correlates strongly with total stand growth. It is further suggested that biomass increment consumes most of the intercepted radiant energy and consequently there are strong correlations between gross-volume increment and LAI. Tree growth and the amount of leaf on a tree are strongly correlated.

Long and Smith (1992) studies of volume increment in *Pinus contorta* var. *latifolia* Douglas concluded that mean leaf area per tree correlates strongly with individual tree growth.

Dean and Baldwin (1996) suggest that to maximize total stand growth, the stand must be managed in such a way that maximum values of LAI are accumulated and maintained. However they also indicate that to maximize individual tree growth, the stand must be managed to promote large crowns on individual trees. Dean and Baldwin (1996) conclude that these objectives are mutually exclusive. However a stand may not be able to gain large values of LAI if other factors such as rainfall are an overarching limiting factor (Pereira et. al. 2004).

Sampson et. al. (1998) points out that fertilizer affects leaf area and that both phosphorus and nitrogen but particularly nitrogen can strongly influence stand LAI. Sampson et. al. (1998) also found that canopy closure and a stand reaching maximum LAI coincide.

The key points about LAI growth relevant to this study are:-

- LAI generally peaks at a species site maximum, then remains constant if undisturbed for some time and can then decline with increasing age,

- A stand fully occupies a site once it reaches maximum LAI for that site and species combination,
- Basal area and LAI are not linearly related throughout the life of a stand,
- Low stocked stands may be unable to fully occupy the site and hence will never reach maximum potential site LAI,
- Tree growth and LAI are strongly correlated,
- With the exception of very open canopy stands LAI has and can be successfully derived from satellite photography provided the issues of spatial scale, positional accuracy, and field sampling intensity are addressed.

Figure 4 demonstrates that a directly linear relationship between stand basal area and LAI for Gngangara plantations has not been found when field data of basal area has been plotted against satellite derived LAI. Unfortunately, much of the water use management carried out on the Gngangara pine (*P. pinaster* Aiton) plantations, for example, management prescriptions in Water and Rivers Commission (2001), before late 2003 assumed that such a relationship existed.

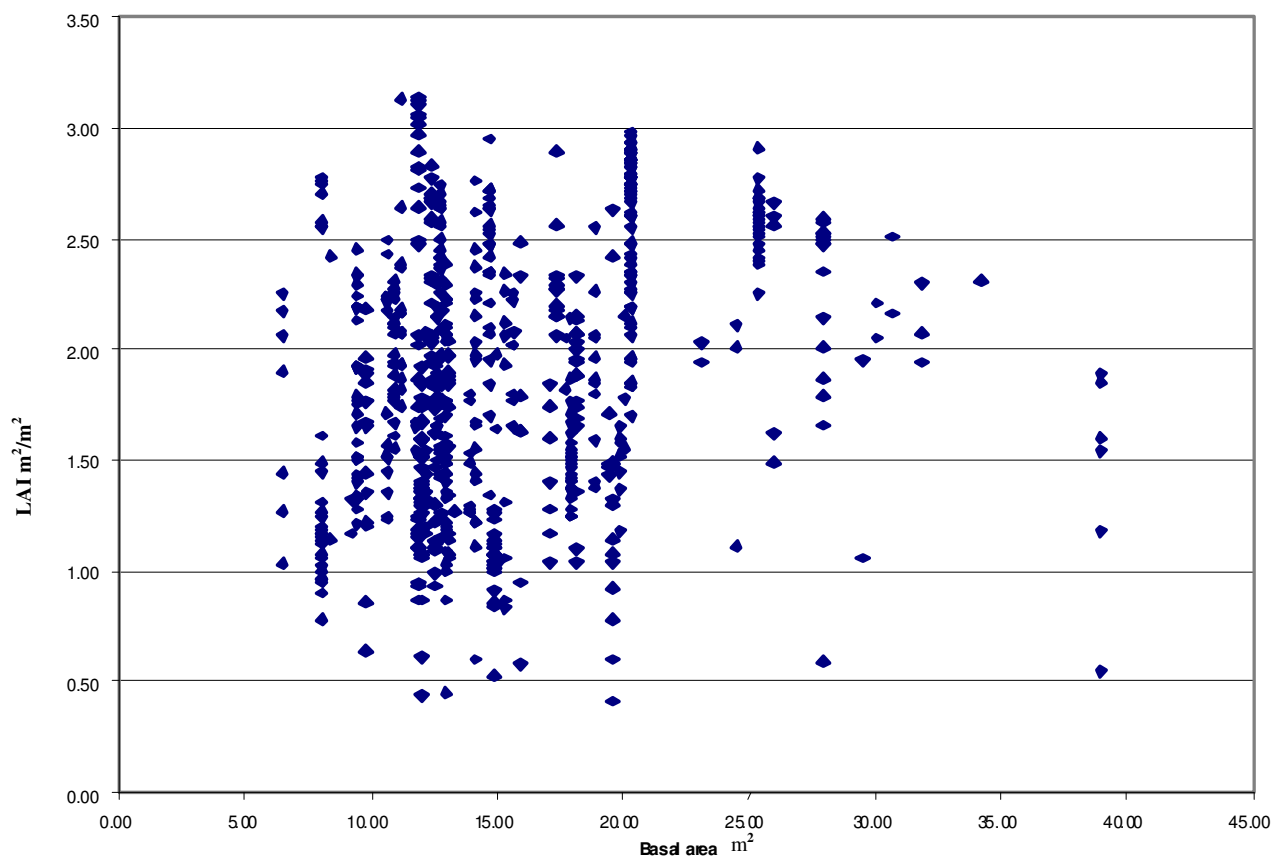


Figure 4. Basal area versus remote sensed derived LAI. Forest Production Commission inventory Nov 2002

### **3. Water Use of Forests and Plantations**

#### **i) Introduction**

Pallardy (2007) contends that the water use by trees is a function of a number of factors including:

- Rainfall
- Species
- Thinning, spacing and pruning management regime
- Variations in age class
- Site productivity, fertiliser application
- Soil type and underlying geology
- Slope
- Period to canopy closure
- Location in the catchment (upland versus lowlands)
- Humidity and evapotranspiration patterns
- Groundwater recharge/discharge locations
- Proportion of catchment planted
- Treatment of riparian zones and drainage lines.

The major factors that can be manipulated by management are the thinning, spacing and pruning regimes. All of these factors influence the time to canopy closure and rainfall interception. Hence, it is important to understand how the management regimes used impact on the plantation water use.

## **ii) How do plantations impact on water?**

Bowyer (2001) suggest that concerns about the negative “impact of plantations on soil moisture and water yield are mostly related to apparent high transpiration rates and impacts on soil moisture depletion, increased moisture interception and evaporation at the canopy level, and reduced stream flow” (p. 325). Bowyer (2001) cites several studies that suggest increased soil water depletion and reduced water yield is not caused by an increase in transpiration, but is due largely to an increased interception and direct re-evaporation of rainfall that is held up in the crown of trees. Calder (1992) suggests the main impact of plantations on aquifer recharge and water yield is increased evaporation. Not all studies show that plantations reduce recharge and runoff. Whitmore (1999) cites several studies that found either no change or higher stream flow associated with plantations as compared to other types of native vegetation. Bowyer (2001) concludes that it does “appear that plantation establishment can have a substantial impact on site hydrology, sometimes positive, sometimes negative” (p. 326).

Lane et. al. (2003) contend that the physical processes driving the greater evapotranspiration from forests relative to grassland can be summarized as differences in aerodynamic roughness, albedo (light reflected), leaf area, rooting depth and ability to extract soil water.

Zimmerman et. al. (1999) suggests that there is a linear relationship with LAI and site water balance (A measure of the amount of water entering and the amount of water leaving a system). Margolis, Oren, Whitehead and Kaufmann (1995) contend that species in a xeric environment, such as Gnamptophaea, need more sapwood per leaf area than in mesic areas, reflecting the greater evaporative demand in xeric environments. Margolis et. al. (1995) further contend that permeability of sapwood explains much of the additional variation found in sapwood to leaf area ratios and the differences are strongly correlated with growth rates and age. Thus, the ratios with a species are reduced on more mesic sites not only because of

differences in evaporative demand but also because of increased sapwood conductivity on more mesic sites (Zimmerman et. al. 1999). Lou et. al. (2002) and Ogawa et. al. (1999) link evapotranspiration to LAI. Both contend that it is an exponential function of LAI.

Medhurst, Battaglia and Beadle (2002) propose that tree water use is driven by vapour pressure deficit, net radiation, wind speed and temperature. It is also influenced by the availability of soil water within the rooting zone (Medhurst et. al. 2002). These variables have an impact on transpiration, which is dependent on leaf area and stomatal behaviour of the species. Medhurst, Battaglia and Beadle (2002) found greater individual tree water use in thinned versus unthinned stands in an 8-year-old *Eucalyptus nitens* H.Deane & Maiden plantation. Greater individual tree water use in thinned stands was mainly due to greater water conductance through the inner sapwood after thinning. Medhurst, Battaglia and Beadle (2002) contend this suggests a change in the transpiration patterns within the crown. The whole stand of trees however used less water in the thinned plots because it had fewer trees. Therefore a “knowledge of the changes to crown structure in particular the rate of leaf recovery after thinning is important for long term prediction of stand water use” (Medhurst et. al. 2002 p. 782). As a thinned stand regrows back towards canopy closure it would be expected that the rates of water use in the individual retained trees would decline to those found in an unthinned stand. This occurs as the retained trees seek to reoccupy the whole site and move back to site maximum LAI and as a consequence, uses up all the water available at maximum LAI. For whole stands as might be expected transpiration was less with increasing thinning treatments, as there are fewer trees even though each individual tree’s water use may be higher in thinned than in unthinned stands. The stands thinned to 100 stems/ha transpired only 23% as much as compared to the 1250 stems/ha in the unthinned control. The stands thinned to 250 and 600 stems/ha transpired 36 % and 55% respectively as much when compared to the unthinned control (Medhurst et. al. 2002).

Teskey and Sheriff (1996) found for 16-year-old *Pinus radiata* D.Don at Mount Gambier that daily transpiration was greater for larger trees than smaller ones but was the same per unit leaf area.

Pereira, David and Madeira (2001) studies of *Pinus pinaster* Aiton in central Portugal demonstrated that transpiration was mainly restricted by soil water availability in this region. Pereira, David and Madeira (2001) found a correlation between cumulative transpiration and cumulative net rainfall. Measurements of stomatal conductance reported in Pereira, David and Madeira (2001) showed an effective control of transpiration losses as the soil dried out and air humidity decreased.

Breda et. al. (1995) conclude that LAI limits transpiration in canopies with high LAI but in open canopies with a low LAI transpiration it was also dependent on climatic factors such as net radiation, wind and vapour pressure deficit. Breda et. al. (1995) found that tree transpiration was not correlated with stem diameter but it was closely related to the leaf area competition index (leaf area of the individual tree/leaf area of all the trees in the vicinity) found directly around the local vicinity of the tree. This suggests that caution is required in relying on estimates of whole stand water use that are derived from individual tree water use measurements. It can be concluded that transpiration is highest when canopies have high LAI's

Meinzer, Clearwater and Goldstein (2001) reviewed recent developments in understanding water transport in trees and concluded that hydraulic architecture and leaf physiology are closely linked and that studies have found considerable functional convergence in regulation of water use across diverse species



The key points that can be summarised about how plantations impact water relevant to this study are:-

- A plantation can impact site hydrology through an increase in evapotranspiration, especially the interception component, with increasing LAI.
- A heavy thinning where more trees are removed does lead to less stand transpiration and interception after a thinning. This gain is lost over time as the stand tries to regain full site occupancy. An understanding of how LAI of a stand changes after a thinning is then important for predicting stand water use and hence recharge.

### **iii) Use of saturated groundwater?**

McJannet and Vertessy (2001) suggest that if summer drought transpiration approximates 20% or less of rates measured in spring then the stand is not using groundwater. Their study found that a *Eucalyptus globulus* Labill plantation on a break of slope position above groundwater at 9.3 metres below the surface was not accessing groundwater and was totally reliant on rainfall.

Teskey and Sheriff (1996) found that daily transpiration was strongly correlated to the available soil water in the upper one metre of the soil. Teskey and Sheriff (1996) suggest that because of this the plantation was not using large amounts of water from deep water sources. For their sites, they found that the soil greater than one metre depth had lower water holding capacity per unit of soil depth than the surface one metre. Teskey and Sheriff (1996) concluded that the issue of whether the pine (*P. radiata* D.Don) was accessing the groundwater, which was eight to ten metres deep at the site, could not be resolved, as they did not have a yearly water balance.

Santiago et. al. (2000) studied transpiration, leaf characteristics and forest structure in *Metrosideros polymorpha* Gaudich stands growing in East Maui, Hawaii. Santiago et. al. (2000) found stand transpiration estimates were strongly correlated with LAI. Whole-tree transpiration was lower on flat sites with waterlogged soils. Trees on waterlogged sites had a smaller leaf area per stem diameter than trees on sloped sites, suggesting that soil oxygen deficiency may reduce leaf area. Thongbai et. al. 2001 contend that an unfavourable aeration of soil with excessive water levels leaves little or no room for gasses, especially O<sub>2</sub> “ (p. 1). Thongbai et. al. 2001 state that “this adversely affects plants by curtailing plant growth and development, decreasing absorption of nutrients and water, changing the oxidation state of mineral nutrients resulting in decreased availability or increased toxicity, and by the formation of toxic compounds” (p. 1). Thongbai et. al. 2001 further state that “the major and immediate effect of waterlogged soils on plant growth is a deficiency of O<sub>2</sub> required for root respiration and growth” (p. 1). Thongbai et. al. 2001 point to this happening “because gases diffuse 10,000 times more slowly in water than in air” (p. 1). Santiago et. al. (2000) also found that transpiration per unit leaf area did not vary substantially regardless of whether the site had more or less leaf area.

Zhang et al. (1999) state that “ the key processes that controls evapotranspiration include rainfall, interception, net radiation, advection, turbulent transport, leaf area and plant available water capacity” (p. ii). “Recharge is the amount of water that reaches a specific groundwater system and it occurs when too much water is available to be used by the vegetation or to be stored in the root zone” (Zhang et. al. 1999 p. 3). It is generally the smallest portion of the water balance and usually derived from precipitation and evapotranspiration measurements. “Recharge and change in soil water storage is often only 5 to 10 % of the annual water balance” (Zhang et. al. 1999 p.3). How much water a plant transpires is related to its leaf area. Leaf area also affects the amount of interception of rainfall, the amount of radiation captured

and it defines the canopy area available for evapotranspiration. “During wet seasons, plants extract most water from shallow layers where the root density is the highest. As the soil dries progressively, more water is extracted from deeper layers to keep stomata open. Rooting depth determines the soil volume which plants are able to draw water from and together with soil hydraulic properties; it defines the plant available water capacity.” (Zhang et. al. 1999 p.10)

Canadell et. al. (1996) contend that average maximum rooting depth was about 7 metres for trees, and 2.6 metres for herbaceous plants. Zhang et. al. (1999) contend that such a difference in average maximum rooting depth would translate into a 540 mm difference in plant available water for sandy soils, and up to three times this amount for loamy and clayey soils. Zhang et. al. (1999) also report Nepstad et. al. (1994) as finding that the soil water stored below 2m provided over 75 % of the total water extracted from the entire soil profile. Zhang et. al. (1999) contend that this indicates that deep roots play an important role in plant water uptake.

Benyon (2002) report reviews current knowledge and research on plantation water use in the Green triangle region of South Australia. He has two cautions in his summary: -

1. “On the basis of recent measurements, it is evident that plantation water use at sites over karst limestone geology is far more variable than was previously thought. (p. iv-v)
2. “Due to gaps in our knowledge on groundwater uptake by plantations, predictions of plantation water use rates at sites with shallow watertables are likely to be accurate only to within hundreds of millimetres per year.” (p. iv-v)

Unpublished studies by Ian Dumbrell and Dr John McGrath of Forest products commission (FPC) indicate a very strong correlation between volume growth and rainfall for *P. pinaster*

Aiton in south west Western Australia (John McGrath 2008, Manager Technical Services Branch Forest products commission pers. comm.).

There are several key points that will need to be taken into account in this study from the discussion above about the use of saturated groundwater. They are:-

- Caution will be needed in transposing some of the findings above, as some of the site characteristics on Gnangara Mound are quite different. For example, unlike the soils at sites studied by Teskey and Sheriff (1996) Gnangara has Bassendean and Spearwood soils that are generally of uniform texture and water holding capacity at depth. Gnangara soils also hold very little water per metre depth. “They are thought to hold up to 25% by volume at full saturation but its field capacity is estimated to be only about 7.5%, this equates to approximately 75mm of water per metre before drainage occurs to lower levels in the unsaturated zone” (Mike Martin 2004, Principal Hydrogeologist Water Corporation, pers. comm.). It appears from Farrington and Bartle (1991) that only approximately 50 mm of the 75 mm per metre of this water is available to *P. pinaster* Aiton.
- The findings above of differences in leaf area on water logged sites point to a need to investigate if there is a difference in leaf area on shallow groundwater areas on Gnangara Mound. Perhaps this could explain why growth rates are slower in the Gnangara sections of the Gnangara plantations, which is shallower to groundwater than either the Pinjar or Yanchep sections. An alternative hypothesis could be that a shallow depth to groundwater means less water available if they cannot access saturated groundwater, as there is less unsaturated soil.
- If volume growth and rainfall are directly correlated then this would confirm that pine plantations are not net users of saturated groundwater.

- If usage of groundwater is occurring this should be shown by increased growth rates on shallow depths to water tables and a lack of correlation of volume growth to rainfall.

#### **iv) Water balance**

Water balance is a measure of the amount of water entering and the amount of water leaving a system.

Wullschleger, Meinzer and Vertessy (1998) reviewed 52 whole plant water use studies on trees carried out since 1970. Wullschleger, Meinzer and Vertessy (1998) suggest that water use per tree should fall between 10 and 200 kg per day for trees that average 21 metres in height.

Eamus (2003) states that “quantification and measurement of ecosystem water balance requires several measures to be used and it is not always easy” (p. 187). Net primary production (photosynthesis minus respiration and hence carbon accumulation) shows much scatter (Eamus 2003). This Eamus (2003) proposes is because there is generally poor knowledge of catchment water availability. Different methods of calculating potential evapotranspiration produce very different results. Net primary production is affected by other factors than water availability. It is also affected by temperature and site factors such as soil fertility, thus adding complexity to the effect of rainfall on net primary production. “Soil depth and soil texture are also important because they determine the water storage capacity of the soil” (Eamus 2003 p. 190). Variation in canopy interception losses also contributes to the scatter found in the relationship between rainfall and net primary production. Eamus (2003) states that ecosystem water balance is only partly determined by rainfall. Eamus (2003) maintains that the characterization of the water balance of a particular site must include some measure of evaporative demand and soil water storage capacity. Eamus (2003) concludes that the database currently available is too inadequate to establish reliable and consistent

relationships between water balance and net primary production over time. The amount of data available for *P. pinaster* Aiton collected from 1968 until 1985 at Gngangara Mound may however be sufficient to develop such a relationship.

The South Australian agency of the Department of Water, Land and Biodiversity Conservation which controls water resources applies an average recharge allowance of 23% for Blue gums *E. globulus* Labill. and 17% for Radiata pine *P. radiata* D.Don. (Department of Water, Land and Biodiversity Conservation South Australia 2008)

Bren and Hopmans (2001) compared pine (*P. radiata* D.Don) plantations and native forests in paired catchments of northeast Victoria. Bren and Hopmans (2001) found that the plantations use less water than the native forests. Bren and Hopmans (2001) also found that the initial conversion of native forest to plantation gave an increase in water yield and stream flow, particularly during the early winter storms. Furthermore, Bren and Hopmans (2001) found that immediately after the plantation was established, there was an increase in run-off of 3 Megalitres (ML) per hectare per year, which slowly returned back to the native forest yields as the plantation canopy closed. Further they found that after the plantation was thinned, water yields increased by 2.21 and 1.87 ML per ha in the first and second years, respectively. Even with the plantations over 20 years old, there was no change in the low- flow frequency between the plantations and native forests' (Bren and Hopmans 2001).

Infocus (2003) cites the work carried out by the Cooperate Research Centre for Catchment Hydrology and their modelling. This indicates that the impact of plantations on water yield will be minimal when: -

- The total plantation area within a catchment is less than 20%.
- Plantations are located in the upper 30% of the land area of catchments.
- Plantations are in rainfall zones below 1,000mm per annum.

- In the 700mm rainfall zone, planting 10% of the total land area of a catchment from the upper slopes down would reduce runoff by less than 10mm per annum or 0.1 megalitre per hectare per annum.

Best et. al. (2003) looked at water yield differences in changes in land use. Best et. al. (2003) found: -

- That establishment of forest cover on sparsely vegetated land decreases water yield and the response to treatment is highly variable and, for the most part, unpredictable.
- Conversion to coniferous and eucalypt cover types cause approximately a 40mm reduction in annual water yield per ten per cent change in forest cover.
- The effect of clear cutting is shorter lived in high rainfall areas due to the rapid regrowth of vegetation.
- Water yield changes are greatest in high rainfall areas.
- In general, changes in annual water yield from forest cover reductions of less than 20% of the catchment could not be determined by stream flow measurement.

Best et. al. (2003) suggested that for a ten per cent reduction in conifer type forest, water yield increased by 20-25 mm, whereas a similar reduction in scrub water yield only increased by 5 mm.

The NSW Department of Land and Water Conservation (2000) point out in most cases the Australian native vegetation is very effective at taking full advantage of any available water. NSW Department of Land and Water Conservation (2000) identified a number of studies, which have demonstrated that-

- Over most of Australia's current dry land grazing and cropping areas the leakage of excess water past native plant root zones is commonly between 1.0 mm and 5.0 mm per year.
- The amount of leakage in areas under agroforestry depends on tree spacings.
- That in low rainfall areas, a typical agroforestry system using 10 metre tree belts at 100 metres spacing would have an annual leakage ranging from 2.0 mm to 10.0 mm, once fully established. This is still much greater than the estimated average leakage of only 0.6 mm per year under native vegetation.
- Leakage rates under mature plantations in the low-to-medium rainfall areas (less than 600 mm per year) are close to zero in most cases.
- Vegetation reduces groundwater recharge by intercepting water before it reaches the groundwater system. It does this by trapping rainwater on leaves, branches and ground litter, from which the water evaporates, as well as through the process of evapotranspiration whereby water is pumped out of the soil by the root system and transpired through the leaves. However, in southern NSW, the persistent winter rain soaks into the soil and then significant amounts of it move past the root zone into the groundwater system. Plant water use and evaporation are limited during this period due to the cold moist conditions. This could be a key issue in the winter dominant rainfall climate of South West Western Australia.
- The amount of precipitation relative to evaporation and water use by plants is the key factor in determining the volume of groundwater recharge.

Petheram et. al. (2000) reviewed 41 studies mainly from southern Australia in low to medium rainfall zones 100mm/yr to 1150mm/yr. In the review the studies soil types varied from very course sands to heavy clays and land-use varied from annual vegetation and perennials and included deep rooted vegetation such as Mallee scrub, Banksia and Pine plantations.



Petheram et. al. (2000) found that the data on water use and recharge from Gngangara Mound in Western Australia was significantly different from other places in Australia and that it required additional analysis to recognise its unique characteristics. Petheram et. al. (2000) described the region as being covered by very deep coarse sands and that recharge estimates were considerably higher (sometimes an order of magnitude higher) than any of those recorded in the literature from other parts of Australia. Petheram et. al. (2000) propose that it is likely that there are different factors limiting transpiration and recharge on Gngangara Mound, such as soil water holding capacity and nutrition to those applied generally to the rest of Australia. Petheram et. al. (2000) claim that the estimator used in Zhang et. al. (1999) for long-term average recharge measurements is inappropriate to use on the Gngangara Mound because of these other factors limiting transpiration.

#### **v) Changes in water use with age of trees**

Apple et. al. (2002) compared needle anatomy of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees across a chronosequence of 10, 20, 40 and 450-year-old stands. Apple et. al. (2002) found differences suggesting a developmental change in needle anatomy with increasing age of the trees. “The percentage of non-photosynthetic area in needles increased significantly with increasing tree age from the chronosequence of 10-, 20-, 40- and 450-year-old trees” (Apple et. al. 2002 p. 129). Apple et. al. (2002) concludes that this reduction in photosynthetic area may contribute to decreased growth rates in old trees.

Hubbard, Bond and Ryan (1999) found that in *Pinus ponderosa* Douglas ex C. Lawson hydraulic conductance was 50% lower in old trees compared to young trees. Whole-tree sap flow per unit leaf area was lower in old trees compared to young trees and mean hydraulic conductance that was calculated from sap flow and water potential data was lower in old trees than in young trees. In addition, leaf to air vapour pressure differences increases caused

greater stomatal closure for older trees than young ones. Yoder et. al. (1994) also found that photosynthesis and stomatal conductance decline more rapidly with increasing saturation vapour pressure deficit in older taller stands.

Eamus (2003) observes that annual net primary production is large and increasing in young forests, but it reaches a plateau at or around canopy closure and declines with age. Young trees have generally higher photosynthetic rates of leaves than older trees. Eamus (2003) attributes this decline to a decline in foliar nitrogen due to its availability having declined and a decline in stomatal conduction caused by increased hydraulic resistance to water transport in tall old trees. Phillips et. al. (2003) suggest that “as trees grow taller, increasing frictional resistance and gravitational potential may reduce leaf and whole-tree photosynthesis by forcing closure of leaf stomata, limiting CO<sub>2</sub> supply to sites of photosynthetic fixation, and decreasing photosynthetic carbon reduction” (p. 237)

Eamus (2003) proposed that an increase in LAI will increase interception losses and the percentage of rainfall interception lost decreases with increasing rainfall intensity. A LAI increase with increasing water availability is a common observation. Canopy interception loss can account for a significant fraction of rainfall. The impact of canopy interception of rainfall is greater in small rainfall events than large ones. It therefore follows that both LAI and the rainfall intensity are an important consideration in determining the input of available water into the soil. Kergoat (1998) suggests that there is a linear relationship between canopy rainfall interception loss and LAI at a more broader annual and regional level.

Kostner, Falge and Tenhunen (2002) found that canopy transpiration per unit of LAI decreased with increasing stand age. That is, older stands need more leaf area to intercept the same amount of water. Bond and Franklin (2002), Alshiemer et. al. (1998), Olbrich (1994)

and Cienciala et. al. (1997) also found that transpiration per unit leaf area reduced with increasing age. Mencuccini and Grace (1996) found that hydraulic conductance declined with increasing tree height of Scots pine (*Pinus sylvestris* L.), potentially lowering canopy conductance. McDowell et. al. (2002) found that for 11 out of 13 species studied leaf area to sapwood ratio declined with increasing height and age of trees.

Battaglia (2001) states “that early in stand development maintenance respiration scales to sapwood volume” (p. 51). However, woody respiration rates per unit sapwood decline in older trees. Apparently maintenance and growth respiration are not independent. It appears that maintenance respiration is higher when growth is higher. Furthermore, Battaglia (2001) goes on to point out that in his review of models no existing model is consistent with all the observations on age related productivity decline. There are also generally higher stockings in younger stands, so both higher individual tree usage and higher stand usage occur.

Studies of other species such as reported by Best et. al. (2003) and Dunn and Connor (1993) show the complexity of the relationships of water use with age. Best et. al. (2003) contend that studies of changes in water yield as a function of vegetation age have shown that the maximum change in water yield may not occur in the first five years after treatment. Their results from paired catchments studies in mountain ash (*E. regnans* F.Muell.) forests of Australia indicate that the maximum water yield changes, when old growth forest is replaced by regrowth vegetation is not seen until approximately 20 years after treatment. The vigorous regrowth in mountain ash (*E. regnans* F.Muell.) forests will cause a decrease in water yield compared to old growth forests. Dunn and Connor (1993) found that for mountain ash (*E. regnans* F.Muell.) the mean of sap velocities did not vary with age and that only stand sapwood area changed by diminishing with age. This finding was used to explain why old

growth forests yield more water than young regrowth forests. Both of these studies show that some caution will be needed to fully understand the relationship of age to water use.

The key points that can be summarised about changes in water use with age of trees relevant to this study are:-

- The age of a stand is an important factor in determining water use as this varies with age.
- Analysis of the age related trends will be required on Gngangara Mound to see if this is an important factor at this site.

#### **vi) Issues in water use calculations.**

Wullschleger et. al. (1998) contends that all the techniques used to determine whole plant water use have both merits and drawbacks. They suggest that before 1990 most forest water balance studies gave unreliable results. Further they contend “There may be some technical problems that confront the hydrologists in scaling up individual tree water use to the stand level” (Wullschleger et. al. 1998 p. 507).

Hatton and Vertessy (1990) and Arneth et. al. (1996) both suggest that there is still much to be learned about the extrapolation process.

Wullschleger et. al. (1998) propose that the best way to determine the transpiration rate of a stand is to measure the water use of every tree in a plot large enough to be unaffected by edge effects. Wullschleger et. al. (1998) point out that this ideal is rarely achieved because of cost and logistic considerations. Hence, there needs to be caution as stand water use estimates must rely on scaling up estimates of water use obtained from only a limited number of representative trees.

Hatton and Wu (1995) investigated the problems associated with temporal scaling in a study of water use estimates of various eucalypt woodlands. Hatton and Wu (1995) found that water use of individual trees was linearly related to leaf area during periods of abundant soil water, as has been observed in previous studies. However, they demonstrated that this relationship was not temporally stable and became nonlinear during periods of water-deficit stress, with large trees transpiring proportionately less per unit leaf area than small trees. Furthermore, the shape of the relationship varied considerably and appeared to depend on soil water status and time of year. This indicates that some measurement results have short-term temporal dependence and cannot be scaled up accurately. Because leaf turnover is slow, but transpiration varies rapidly in response to changing environmental conditions, it is not surprising that temporal mismatches in these two variables should arise. Problems arise when trying to scale up water use using for example, stem diameter because it varies with age. This makes it complicated to estimate how water use varies with age of trees.

Ford et. al. (2004) cast doubt on the reliability of sap flow and sap flux density measurements when used to estimate daily water use. Ford et. al. (2004) found that the expected pattern was not constant through the day or between trees. Ford et. al. (2004) also found that not considering all the factors involved could result in estimate errors as high as 154%. Ford et. al. (2004) found that measuring sap flux density at two distant sample points significantly improved the estimate of daily water use but even this was subject to errors as great as 32% in individual trees. “The variability in sap flux density with depth into the xylem, over time and between trees indicates that radial measurements of sap flux density are necessary to accurately estimate water flow in trees with large sapwood areas” (Ford et. al. 2004 p. 241). Medhurst et. al. (2002) also found large radial variation in sap velocity.

Potential evaporation is a measure commonly used to assess site water balance. Eamus (2003) contends that calculation of potential evaporation using the Penman equation always overestimates evaporation and therefore underestimates runoff. A review carried out by Vorosmarty, Federer and Schloss (1998) found different methods of estimating potential evapotranspiration can produce results that differ by hundreds of millimetres and that the differences are greatest between models in hot dry climates.

The key points that can be summarised about issues in water use calculations relevant to this study are:-

- Much doubt exists about whole plant and stand water usage calculations, particularly those reliant on up scaling.
- Up scaling of sapflow measurements appears to be unreliable.

#### **vii) Water modelling**

Zhang et. al. (2003) attempted to predict the impacts of afforestation on water availability in the Goulburn-Broken catchments in Victoria. Zhang et. al. (2003) contend that the age of the trees contributes to the observed water yield changes. Maximum water yield reduction is not always achieved in plantations due to thinning, harvesting, and other management practices. Zhang et. al. (2003) attempted to account for this by relating water yield reduction with plantation age and site conditions using a plant growth model (3PG) as described by Landsberg and Waring (1997). From the 3PG model, Zhang et. al. (2003) were able to predict stem carbon and then convert this to an estimate of stem volume once an allocation was made for branches and bark. Other growth attributes generated at 5-year intervals were stand volume, mean annual stem growth increment and LAI. The model calculates the monthly water use using the Penman- Monteith equation as described by Monteith (1981). An estimate of available soil water storage is made using an understanding of soil properties. Zhang et. al.

(2003) did not rely on extrapolation of growth predictions beyond 25 years old, as the parameterization was based on young trees. The LAI values they obtained from the model when plotted against age showed exponential growth up to a maximum point at an age between approximately 8 and 16 depending on the site quality type. It then declined from between 25% to 50% from that point. This is different from what is described by other authors in the literature. It is unclear whether there was any attempt by Zhang et. al. (2003) to compare the results of their modelling for *E. globulus* Labill. against field measurements of the LAI trend with age results.

Morris (2002) point out that 3PG models were designed to predict growth. Prediction of stand water use is incidental to this. Applications of 3PG to predict stand water use are relatively untested. Validation is therefore required before water use predictions can be confidently relied upon using this model. Forty-eight parameters per tree species are defined in the model. This large number of parameters could lead to some combinations of them producing an accurate growth prediction but may provide an inaccurate water use estimate. Hence, there is a need to validate the model water outcomes against field measurements of water use and stand growth simultaneously. Morris (2002) reports that, at that time of writing, data including measuring monthly stand water use had been collected for the previous 18 months to aid in the validation for a range of major eucalypt species across the climatic range in Victoria. Sands and Landsberg (2002) compared modelled versus observed parameters for *E. globulus* Labill and concluded that 3PG could adequately predict stem growth rate but not LAI in its configuration at that time.

Mohammed (2003) describes CABALA as a dynamic process-based growth model developed by Hobart-based scientists Dr Mike Battaglia and Dr Peter Sands. The model predicts wood volume growth based on factors such as rainfall, temperature and soil type. At the same time,

it shows how other stand features such as leaf area index, crown length and the distribution of tree sizes are likely to develop. Battaglia, White and Mummery (2002) used CABALA to predict the growth and the development of water stress in modelled plantations. Battaglia, White and Mummery (2002) show how the model may be used to develop silvicultural prescriptions and management regimes to reduce the risk of drought death in plantations.

The Perth Region Aquifer Modelling System (PRAMS) (Water Corporation 2002) is described as “A system for simulation of aquifer behaviour in response to input (eg rainfall) and output (eg pumping) changes”.

PRAMS is based on WAVES as described by Dawes and Short (1993) and Zhang, Dawes and Hatton (1996).

Zhang, Dawes and Walker (1999) point out that “many models that incorporate all the relevant factors to forest growth and water use and the detailed processes and feedbacks have been developed, e.g. WAVES (Dawes and Short 1993; Zhang et. al. 1996), SCAM (Raupach et. al. 1997), SiB (Sellers et. al. 1986)” (p. 21). Zhang, Dawes and Walker (1999) contend, “these models are useful in exploring sensitivity of the system” (p. 21) “However, they may have little practical value for catchment studies because the interactions and feedbacks between processes are not yet fully understood, and the data required to calibrate and run them are not available” (Zhang et. al. 1999 p. 21).

Vertessy, Silberstein and Hatton (1999) point out that for the previous decade, “a vigorous debate has been running about the utility of physically-based models in hydrology” (p. 30).

Vertessy, Silberstein and Hatton (1999) point out that critics have argued that such models: -

- Cannot be adequately ‘parameterised’,



- Cannot be ‘validated’,
- Use inappropriate descriptions of physical processes, and
- Confer dubious advantages over simpler conceptual models.

Vertessy, Silberstein and Hatton (1999) highlight problems in model parameterisation and reality checking. Vertessy, Silberstein and Hatton (1999) contend that complex models demand detailed information on the properties of the site it is being applied to such as:-

- Topographic data,
- Climate data,
- Vegetation data,
- Soils data and
- Aquifer data

Vertessy et. al. (1999) further point out that “some advocates of physically-based hydrologic models have projected their software as crystal balls, setting up the expectation that they can predict something that we are unable to see in nature” (p. 31). Vertessy et. al. (1999) also “prefer to think of them as powerful calculators, acknowledging that they can do no more than mimic our formalised perceptions of how hydrologic systems work” (p. 31). Vertessy et. al. (1999) found however, “that they are very useful in highlighting interesting process feedbacks which are not otherwise apparent” (p. 31). Vertessy et. al. (1999) argue however that these problems do not necessarily totally devalue complex models and that they can be used to test a variety of hypotheses of plantation hydrologic function. Vertessy et. al. (1999) “stresses the need for improved field measurement techniques and continued experimentation, proceeding hand in hand with model application and testing” (p. 30). Vertessy et. al. (1999) “conclude that uncertainty will always surround predictions obtained using models of this kind” (p. 31).

Calder (1998) questions whether using complex models is the only answer to understanding forest evaporation. Historically Calder (1998) points out models have worked best in wet

temperate climates. Calder (1998) points out that in dry environments evaporation is more limited by supply than meteorological demand. Calder (1998) postulates that studying limitations may be a better approach. Calder (1998) proposes that a drive to increase the realism in general biophysical models has led tree physiologists to build complex models that are increasingly difficult to apply to real world water resource problems. Calder (1998) presents arguments that point to a need to supplement or use as an alternative the knowledge of the limits that may be controlling water use in a specific environment.

Concerns with regards to the reliance on the modelling (PRAMS) carried out on Gwangara Mound to that time were raised by Peer Group Review (2002). “None of the modelling described in the draft report has been documented in separate reports, or if so, no references have been provided and we have been unable to review them. Much reliance is being placed on modelling, as a tool that will help us in the future. Yet the models are being used already to influence decisions, without having been fully developed, documented and tested” (Peer Group Review 2002 p. 2). In response to this report, it was acknowledged that the modelling at Gwangara Mound being undertaken was still in the developmental stage, particularly the Vertical Flux Model (VFM) component (Response to Peer Review Panel Comments 2002).

Polglase (2003) state “the overwhelming point that has emerged is the need to recognise the diversity of ecosystem specific processes and impacts that are relevant to local and regional economic, environmental and social contexts. It is therefore imperative that the forestry and water debates be guided by balanced analysis including science, economics policy, politics and community needs” (p. 1).

The key points that can be summarised about water modelling relevant to this study are:-

- There are concerns as to the reliability of complex water models, including PRAMS.

- A focus on limitations on forest and tree growth is needed to both test and supplement the provision of knowledge in the situations where complex water models are used.

## 4. Factors affecting tree growth with specific references to *Pinus pinaster* Aiton

### i) Growth

Pretzsch (2009) contends that the following factors have important effects on tree growth -

- Climatic conditions
- Site conditions (including nutrition)
- Initial spacing and treatment
- Silvicultural treatment

Briffa (1994) who studies where in northern Fennoscandia(Norway) contends that a complicated mix of climate and site factors controls tree growth. These include soil and air temperatures, soil moisture conditions, sunshine, wind, soil depth, soil texture, soil fertility, and topography. Impeding layers such as bedrock, coarse gravel or excess soil moisture may restrict rooting depth. Deep soils are better for tree growth than shallow soils because they are generally more fertile and have a more favourable soil moisture regime. Briffa (1994) points out that growth varies according to how the combination of these edaphic and climate factors changes throughout a growing season and through the life of a plantation or forest.

Additional complexity results from the fact that tree growth in one year is influenced by the nature of growth in one or more previous years and even by the climate conditions that prevailed outside the growing season. *P. pinaster* Aiton produces its next season's needles in the season prior to the current growth year (John McGrath, Manager and Ian Dumbrell Forest Scientist 2008 Technical Services Branch Forest Products Commission pers. comm.). The new needles, and hence part of the current season photosynthetic effort is dependent on the previous one. A drought in one year consequently has an impact not only in that year but also

in the following one because fewer and smaller needles were laid down. Development of the tree over a number of years is also affected by non-climate-related factors that include tree age, competition from other plants, soil fertility and attacks by insects.

Pretzsch (2001) conclude that in addition, inter-seasonal and intra-seasonal factors need to be considered-

- In any one growing season, different parts of a tree start growing at different times.  
Different species may also react differently.
- Usually, height growth precedes any diameter growth or needle flush.
- The progression of terminal bud extension (main stem and branches) is basipetally, i.e. extension growth starts at the top of the tree and progressively moves downwards towards the base.
- The amount of height growth in any one season depends on hereditary factors, immediate past environmental conditions and present environmental conditions.
- Diameter growth also proceeds basipetally and is much more related to current foliage and present environmental conditions.

A further important characteristic of tree growth is that all growth of new tissue takes place at only specific areas on the tree, by the division of specialized cells called meristems (Ward 2006). These actively growing areas are located at the tips of branches and roots and in a thin layer (the cambium) adjacent to the bark.

## **ii) Growth stages and relationship to age**

Norby et. al. (2001) suggests that “young trees undergo a period of exponential growth in which an increased leaf area supports increased growth, which in turns supports production of

more leaf area (p. 477). As the trees grow into a forest stand, leaf area reaches a relatively constant value as it becomes constrained by environmental limitations imposed by available water, nutrients, or light (p. 478). Exponential growth is no longer possible, and trees enter a linear growth phase in which their growth increment is approximately constant each year” (p. 478). Eventually growth will decline when trees reach a sufficiently large age.

Pretzsch (2001) recognizes a number of relationships between growth and age.

1) The size to age relationship for a tree can be represented by a cumulative growth curve, which is sigmoidal. There are three distinct phases in this relationship (Figure 5) :-

- Juvenile phase (youth) - accelerating rate of growth
- Mature phase (maturity) - constant rate of growth.
- Senescent phase - decelerating rate of growth

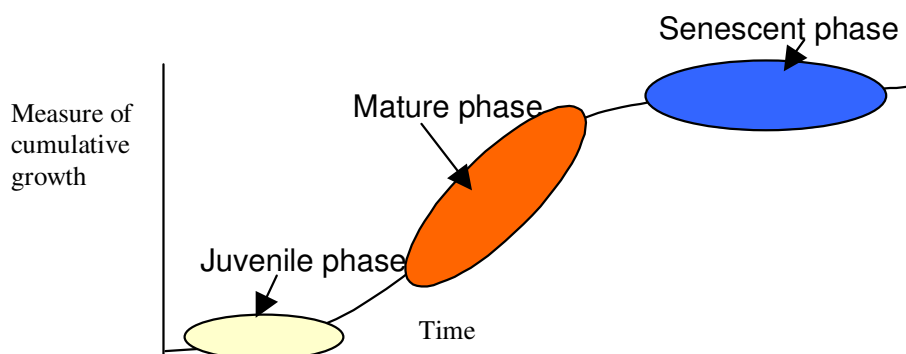


Figure 5. Growth phases

2) The diameter to age relationship for an individual tree varies from a linear to concave curve depending on species, environment and silvicultural treatment Pretzsch (2001).

3) The height to age relationship usually reflects clearly the inherent vigour of the tree and the environmental conditions under which it is growing. For this reason, this relationship is a common basis of site classification Pretzsch (2001). The height to age relationship for Gngangara Mound *P. pinaster* Aiton is shown in Figure 6.

4) The volume to age relationship is sigmoidal, but it often varies because of the effect of climatic changes and silvicultural treatment. The cumulative growth curve usually shows a long early period of curvilinearity, a linear trend becoming evident much later than is found with the diameter/age and height/age relationships Pretzsch (2001).

5) The increment to age relationship is represented by the increment curve. Pretzsch (2001) contends that the natural increment phases of juvenile, mature and senescent are of extreme importance to the science of forest yield.

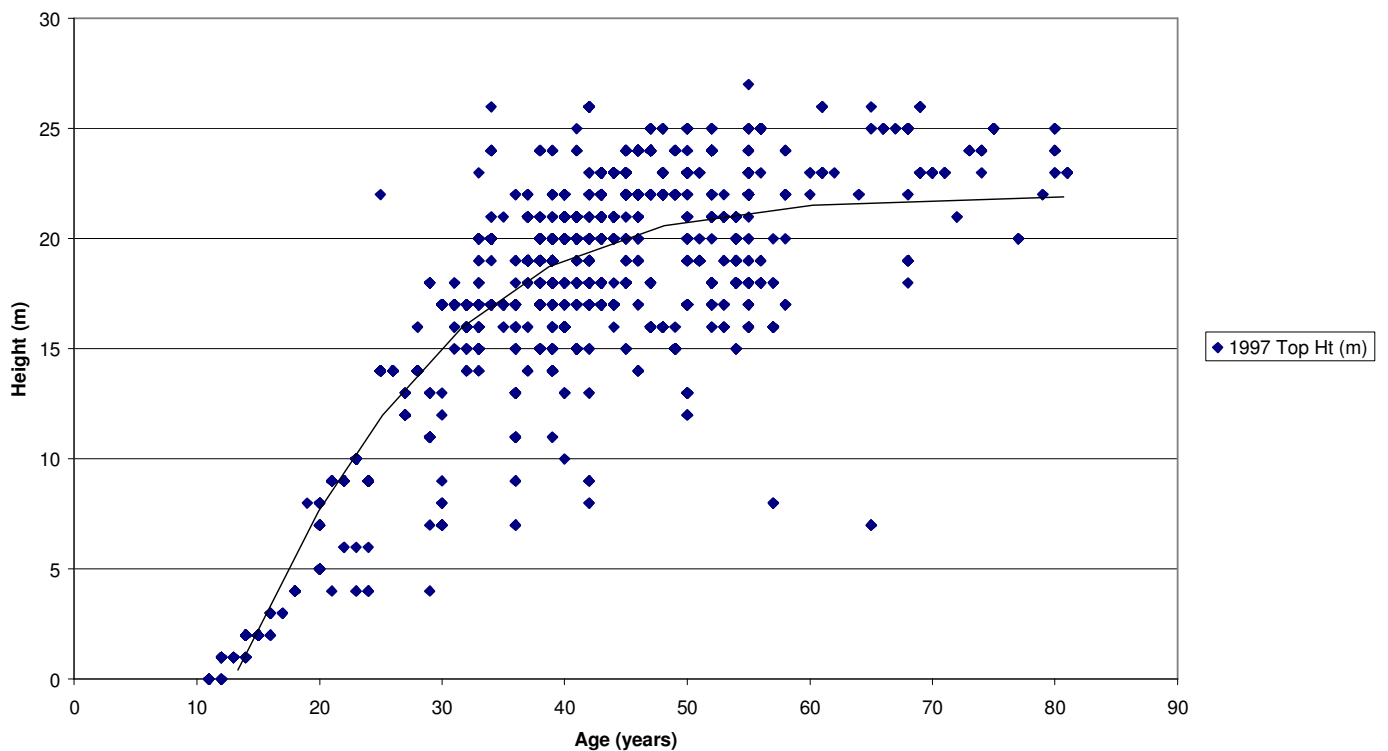


Figure 6. Top height vs. age from Gwangara *P. pinaster* Aiton plantations Forests Production Commission (1997 data from complete stand inventory)

### iii) Growth increment

There are two common expressions of increment, current annual increment (C.A.I.) and mean annual increment (M.A.I.). Pretzsch (2009) defines current annual increment (CAI) as the increment over a period of one year at any stage in the tree's history (Figure 7). The CAI varies from year to year being affected by seasonal conditions and silvicultural treatment. For this reason, it is common practice to express the increment as a mean over a period of years, termed the periodic mean annual increment (PMAI or PAI).

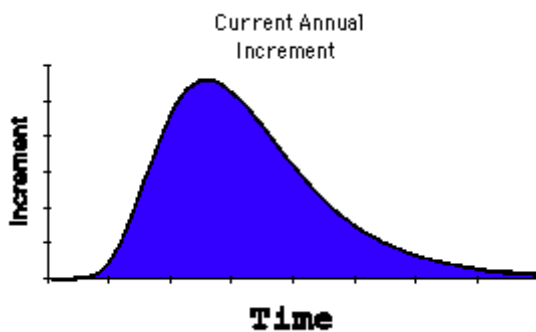


Figure 7. Conceptual current annual increment curve

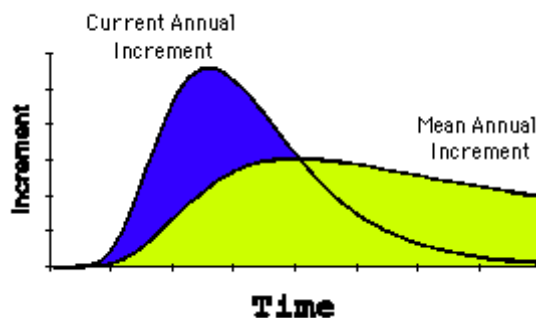


Figure 8. Conceptual current annual and mean annual increment curves.

Pretzsch (2009) define mean annual increment (MAI) as the average annual increment over the whole period from origin to a specific age (Figure 8).



Pretzsch (2009) propose that the increment is determined by the pattern and rate of growth of the tree and varies with:

- Species
- Internal conditions (genetic and physiological)
- External conditions (climatic, edaphic, biotic).

Incorrect predictions of tree growth and development may occur if the average increment figure is not related to the general climatic conditions that prevailed during the period of measurement. The data are also meaningless unless it is also related to tree age or size.

#### **iv) Limiting factors.**

Grissino-Mayer (2003) recognizes a number of principles of growth. Of these, the principle of limiting factors is a critical consideration in understanding tree growth. Grissino-Mayer (2003) defines it as “the rates of plant processes can occur only as fast as allowed by the factor that is most limiting” (p. 1). For example if the most limiting factor is rainfall then the amount of wood produced by a tree will mostly reflect the amount of rainfall that fell.

Pretzsch (2009) contends within limits the more growing space made available to a tree, the less competition it will face and the faster it will grow. It follows that the efficient management of a forest requires careful regulation of stand density, which is broadly defined as a quantitative measure of tree cover on an area. An understanding of the degree of utilization of growing space available for tree growth is essential in the analysis and estimation of forest growth and yield. Dean and Baldwin (1996) state that “during the interval a stand fully occupies a site, the scarcity of resources suppresses recruitment and reduces individual tree growth to a minimum through competition” (p. 1). However maximum stand productivity results at full site occupancy because the stand consumes all the resources supplied by the site.

Irvine et. al. (2002) states that “drought limitations to carbon assimilation” and hence growth “have been extensively studied, and the inclusion of water limitations in models of forest productivity is now widespread” (p. 195).

The effect of thinning is to accelerate diameter growth of individual trees by creating more growing space and allowing more radiant energy that stimulates increased growth in crowns and boles. The increase in growth that occurs depends on the degree of suppression prior to thinning (Pallardy 2007).

Breda, Grainer and Aussenac (1995) state that studies of coniferous tree species have shown that thinning results in increased tree growth because the rainfall input is distributed to fewer trees. The increase in available water to individual trees is brought about by both reductions in interception and transpiration at a stand level (Breda, Grainer and Aussenac 1995). This change was a direct function of stand leaf area decrease because of the thinning which lead to a proportional reduction of transpiration divided by potential evapotranspiration (Breda, Grainer and Aussenac 1995). Benyon et. al. (2004) state that LAI is reduced by thinning and hence if applied appropriately can reduce water use of plantations. Benyon et. al. (2004) further suggest the possibility that there is some net recharge for a period after thinning. Stape, Binkley and Ryan (2004) found that *Eucalyptus* stands in Brazil on average increase LAI by 0.3 units per each additional 100 mm per year rainfall. Even in the tropics, they found that water was one of the limiting factors in growth rates achieved in above ground net primary production in eucalypt plantations.

Sudmeyer (2002) found that trees growing on the edge of belts or blocks benefit from increased access to light, water and nutrients via roots extending into the adjacent land. The economics of timber production can be improved by taking advantage of increased growth of edge trees. Sudmeyer (2002) reports on two examples from the Esperance area to illustrate the

benefits of growing trees in belts. At one site the MAI (Mean Annual Increment) of 8 row belts (inner and outer trees) was 22 m<sup>3</sup>/ha/yr for the outer tree compared to an MAI of 12 m<sup>3</sup>/ha/yr for the inner trees, at another site the MAI of a 12 row belt was 10 m<sup>3</sup>/ha/yr for outer trees compared to 5 m<sup>3</sup>/ha/yr for the inner row trees.

Cienciala et. al. (2002) found increases in tree water use and growth increment was greater for tree in an edge zone than those within an interior of Scots Pine (*Pinus Sylvestris* L.) stand grown on poor sandy soils.

York, Battles and Heald (2003) observed edge effects and their impact on increases in mixed conifer sapling height growth. York, Battles and Heald (2003) concluded that the increases in height growth were correlated with the increase in light and water supply at the edges of cleared openings.

#### **v) Stand increment**

Zeide (2001) discusses the history of the thinking behind the principles used for thinning and understanding growth in forests. Zeide (2001) contends that in the 18th century when forestry was systemized the principle objective was not to increase productivity but to safeguard the trees. Thinning at this stage in the development of stand management principles resulted in an unregulated harvest that left stands depleted. This approach to management lead to the belief that productivity increases with increasing numbers of trees and reaches a maximum in undisturbed dense stands with complete crown closure. It was only when a system of protection from inappropriate thinning was introduced that it became possible to consider thinning that anticipates natural mortality (Zeide 2001). Later theories, such as those proposed by Mar:Moller (1954) and Langsaeter (1941), which have been widely accepted by forest scientists and managers, demonstrated that thinning redistributes the growth from the smaller

trees to the larger trees without loss of total volume provided the density of trees remains above the critical level needed to optimally occupy the site. The “Moller plateau” and “Langsaeter curve” show that when stand volume increment is plotted against stocking or basal area, it is constant over a wide range of stand densities (Figure 9).

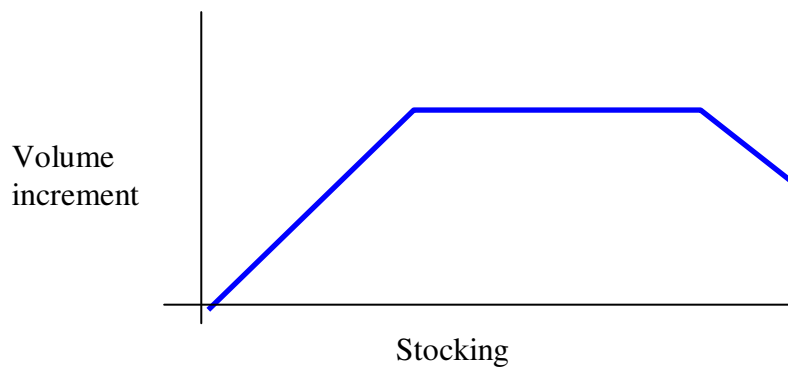


Figure 9. Simplified diagram of “Moller Plateau”

#### vi) Gngangara Mound *P. pinaster* Aiton stand increment

A significant number of studies have been carried out on the factors affecting growth of *P.*

*pinaster* Aiton. Hopkins (1971) showed that diameter growth response in 19 year old *P.*

*pinaster* Aiton at Gngangara Mound was immediate following thinning release and was three times greater for stands thinned

Butcher (1999) found for *P. pinaster* Aiton at Gngangara Mound that planting at 1500 stems per hectare (stems/ha) and thinning to 500 to 600 stems/ha at age 18 would maximise volume production. Butcher (1999) also demonstrated that thinning down to between 400 and 500 stems per hectare between age 14 and 20 would achieve optimum production of larger log piece sizes but with a total stand volume loss of 20%. For ages 20 to 30 and 30 to 40, Butcher (1999) found that the optimum large log size was obtained at stockings of 250 to 350 stems/ha and 150 to 250 stems/ha respectively.

Butcher (1999) found that *P. pinaster* Aiton stands had a similar relationship between volume increment and stocking to that proposed by Mar:Moller (1954) and Langsaeter (1941) as his study data showed when volume was graphed against stocking it formed a plateau.

Late thinning studies in *Pinus pinaster* Aiton were carried out to determine the relationship between thinning at age 17 years and 6 stocking levels (2,500 unthinned control, 1000, 700, 485, 400 and 280 stems/ha) (Hopkins and Butcher 1999b). The thinning between to 700 and 480 stems per hectare at age 17 approximates the current practice, which is first thinning to 600 stems per hectare at age 18 to 20. At age 35, they found no significant total stand volume differences of stands with stockings of between 2500, 1000 and 700 stems/ha. Hopkins and Butcher (1999b) also found, apart from immediately after thinning in the 17 to 19 year growth period, that there were no significant treatment differences in volume increment of the whole stand except for the 31 to 33 year growth period (Figure 10).

Hopkins and Butcher (1999b) found that the mean annual increment, when measured at age 35, for total volume production (standing volume plus 1957 thinnings in m<sup>3</sup> ha<sup>-1</sup>) was not significantly different over the range of stockings from 2500 to 480 stems/ha. There was however, significantly different lower growth in the 400 and 280 stems/ha plots compared to the higher stocked plots. This demonstrated that thinning below 480 stems/ha at age 17 left the stand unable to fully occupy the site until age 35. The maintenance of growth increment equivalent to the pre-thinning stocking for the stands above 480 stems/ha are achieved because the trees left are able to rapidly reoccupy the site and therefore capture the same radiant energy as the pre thinned stand. This characteristic of stand dynamics is important because it makes it possible to increase the size of individual trees with no loss of total growth. Zeide (2001) contends that consensus on a plateau type effect is not universal and that some still believe that any reduction in growing space must reduce total volume production. Curtis, Marshall and Bell (1997) thinning studies for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) results contradict Langsaeter's hypothesis of constant increment across a

wide range of stockings.

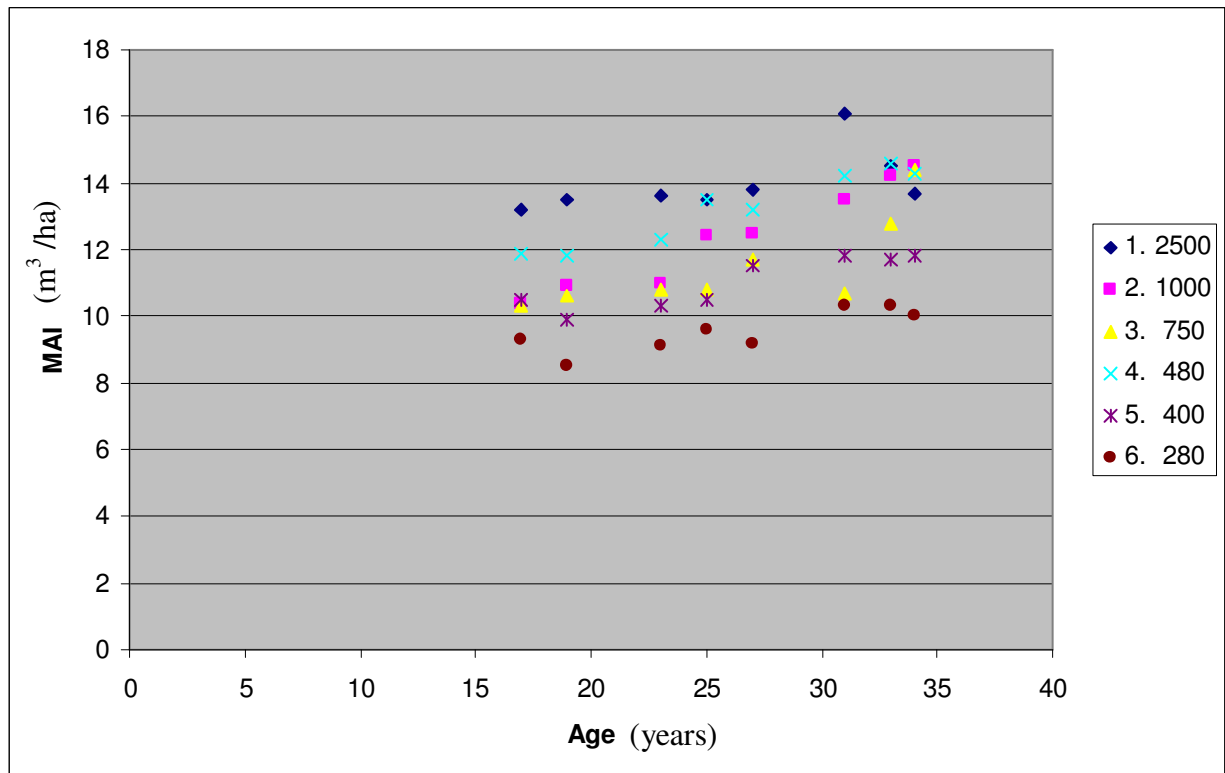


Figure 10. Mean annual increment for total volume production (standing volume plus 1957 thinnings in  $\text{m}^3/\text{ha}$ ) for the original 18 plot design from Hopkins and Butcher 1999b. Treatments 1 - 2500 stems/ha, 2 - 1000 stems/ha, 3 - 750 stems/ha, 4 - 480 stems/ha, 5 - 400 stems/ha, 6 - 280 stems/ha.

Zeide (2001) points out though that an increase in total volume increment at higher stocking levels is unlikely to apply to merchantable volume, because increases in stand density may decrease individual tree size below a merchantable limit and so it must at some point decline before full site occupancy. Zeide (2001) states, “we have after centuries of study learned that thinning from below can increase merchantable volume but not total volume increment of tree stands” (p. 24). The reason for this is that the loss of total stem volume is more than compensated by the value of increased merchantable volume obtained and that there are other benefits such as increased supply of soil water.

Hopkins and Butcher (1999a) also found this for *P. pinaster* Aiton on the Gngangara Water Mound in their basal area thinning trials. Plots thinned down to  $7 \text{ m}^2$  basal area had twice the

volume in the select crop trees as those at 37 m<sup>2</sup> basal area despite the total production in the 7 m<sup>2</sup> plots being half of that of the 37 m<sup>2</sup> plots.

Butcher (1977) also showed an increase in effective rainfall (rainfall minus interception) of approximately 15% in the 7 m<sup>2</sup> basal area plots as compared to the 25 m<sup>2</sup> plots.

Butcher (1977) concluded that the major factor determining *Pinus pinaster* Aiton growth on the Gngangara Mound is soil moisture availability which in turn is determined principally by:-

- The depth of the unsaturated porous sand because this limits the rooting depth and hence the quantity of available water storage during winter. This is because the roots will not grow into the saturated sand zone.
- The density of stand because this controls the rate of usage of the stored water during the spring and summer season.

When stands are thinned this reduces the stand density and hence increases the through fall (because of increased interception) of rain and hence the recharge of the soil moisture system. At a lower stand density there is also a reduction of water withdrawal from soil moisture over the long summer drought period when compared to that prior to the thinning.

#### **vii) Evidence on the relationship between growth rates and water table depth on the Gngangara Mound**

A review of the large amount of inventory data and satellite derived LAI data was undertaken in order to determine the impacts on stand growth of differing depths to water table.

Inventory data was available from 1992, 1997 and 2002. Satellite derived LAI was available at approximately 2-yearly intervals from 1988-2003 and then yearly from 2003 to 2007.

Depths to water tables in 2002 were derived from data provided from the then Water and Rivers Commission (Figure 11). Representative components of the plantations with similar

treatments were then identified from the above data to investigate the relationship between growth and depth to water table. The findings are summarized below.

Gnangara plantation has a lesser depth to water table on average than both Pinjar and Yanchep (Figure 11 and Figure 12). Gnangara, however, has lower than average growth rates than both Pinjar and Yanchep (Table 1). Tree growth at Pinjar and Yanchep is at least 33% higher even though there is a rainfall decline from south (Gnangara) to north (Pinjar and Yanchep) of the plantation estate of approx 100mm per annum.

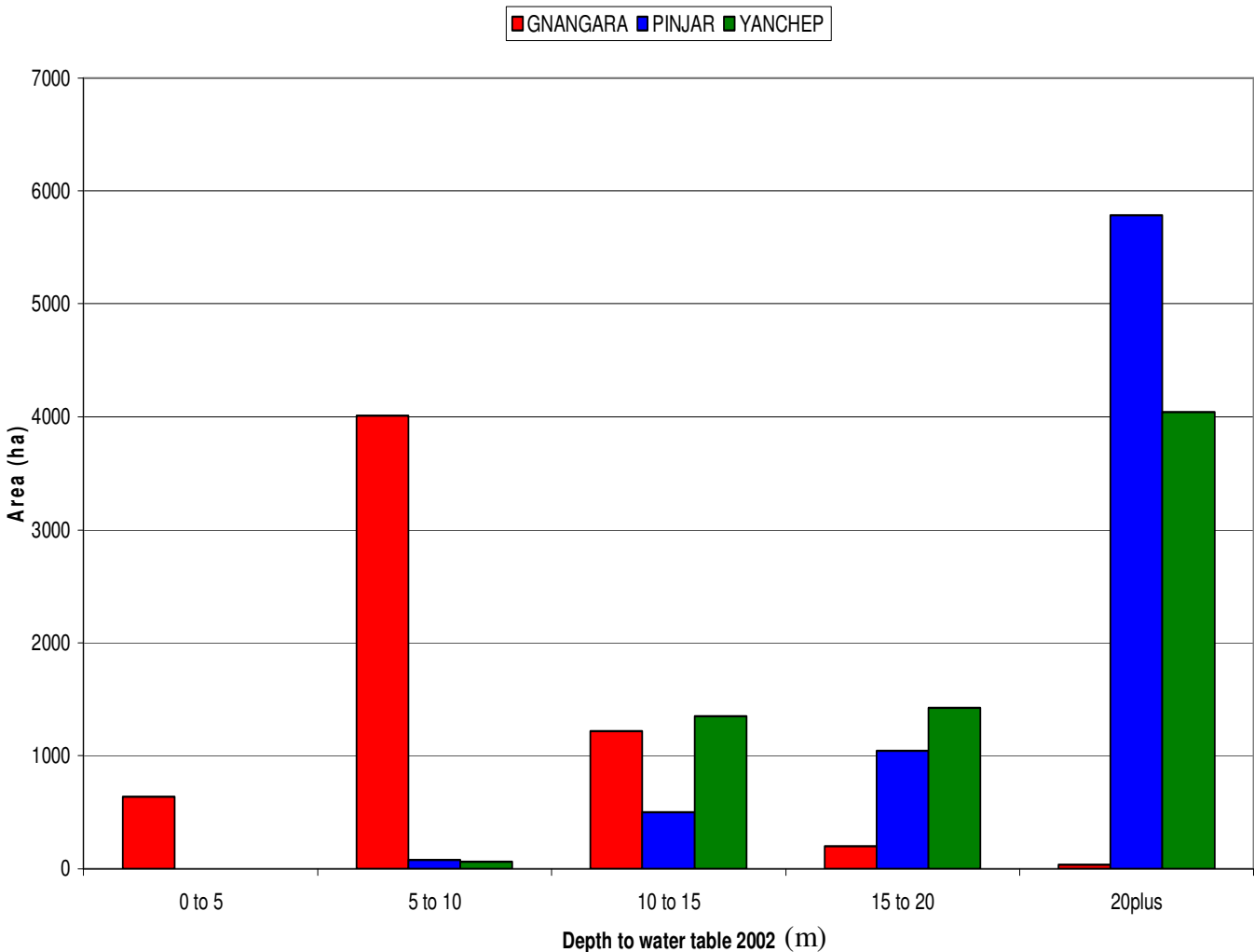


Figure 11. Depth to water tables 2002 areas by plantation, Source Waters and Rivers commission



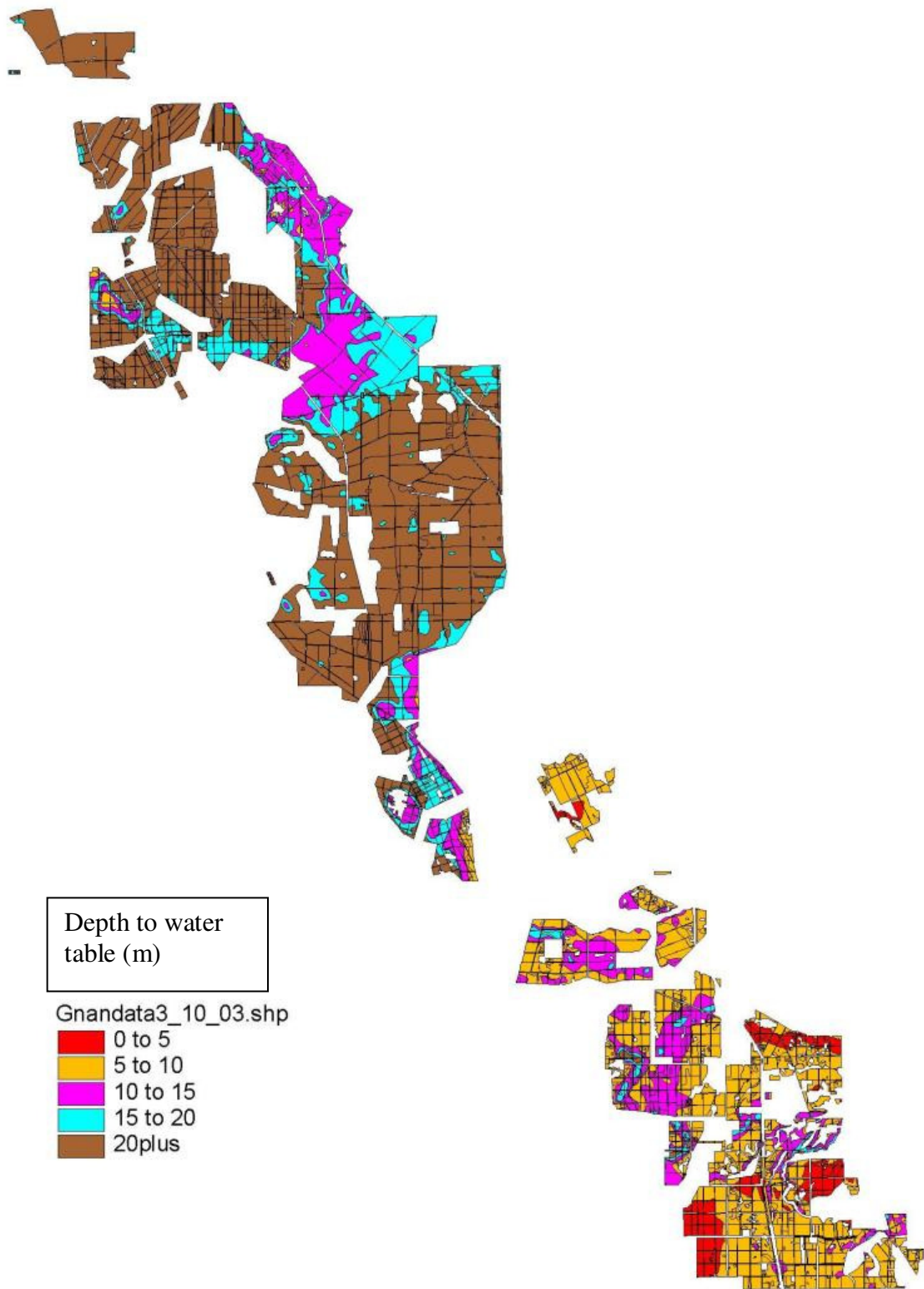


Figure 12. Depth to water table at the end of summer 2002 below Gngara Mound plantations, information provided Department of Water

Table 1. Summary of recorded growth rates for plantations on the Gnangara Mound, Source FPC 2002

	Average CAI m <sup>3</sup> /yr		Average annual rainfall (mm)
	Gnangara	Pinjar/Yanchep	
1992 to 1996	6	10	782
1997 to 2002	5	7	738
1992 to 2002	6	8	758

Further evidence of the relationship between water and tree growth is shown by the relationship between rainfall and growth. Rainfall declined between 1997 and 2002 when Perth had a number of drought events during this period, which correlated with a decline in tree growth (Figure 13).

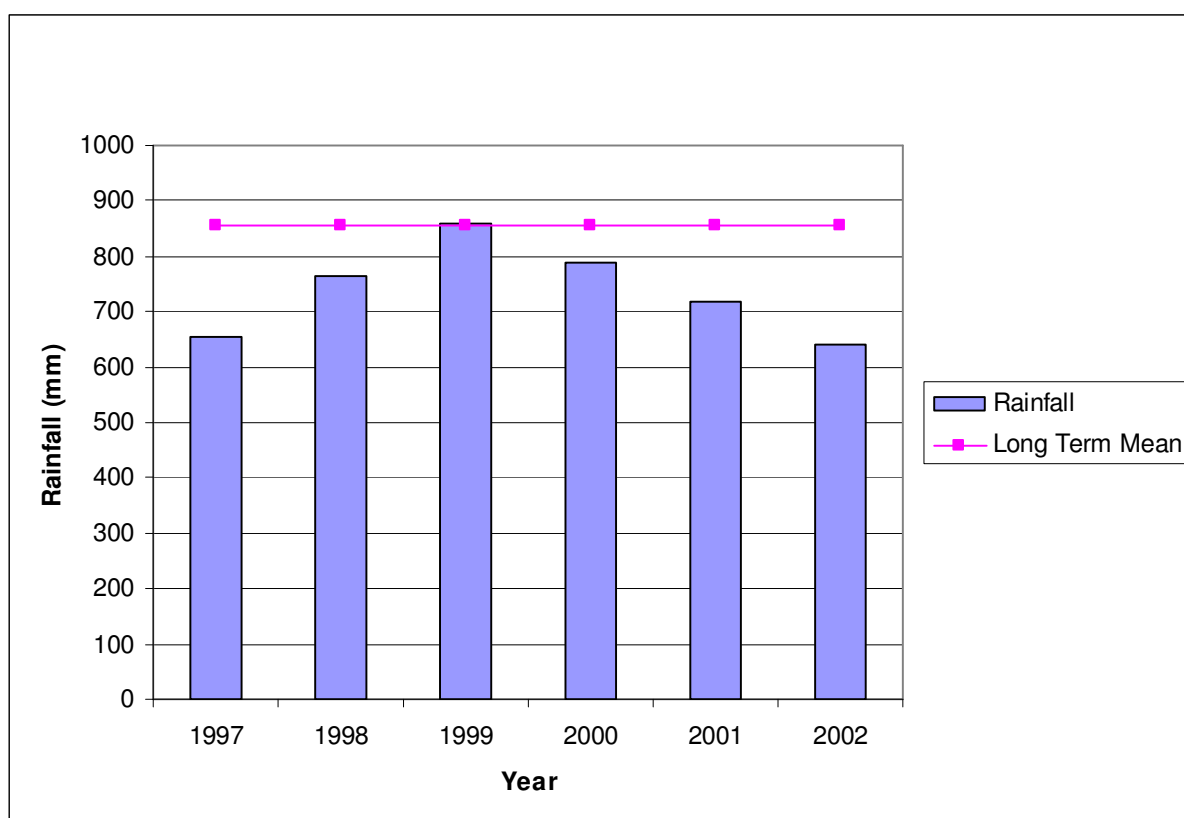


Figure 13. Annual rainfall for Perth from 1997 to 2002

These observations indicate that growth is strongly correlated to rainfall. McGrath, Harper, Dumbrell and Robinson (2002) state that “in the seasonally dry Mediterranean climate of south-western Australia, plantation productivity is strongly linked to water availability” (p.

361(1)). The relationship they found between rainfall minus evaporation and MAI is linear. Studies conducted to determine growth across a range of rainfall sites for *P. pinaster* Aiton show a linear relationship for *P. pinaster* Aiton growth to rainfall alone (John McGrath, Manager and Ian Dumbrell Forest Scientist 2008 Technical Services Branch Forest Products Commission pers. comm.).

Further work looking at water use on Gngangara Mound has been undertaken by Ian Dumbrell (Research scientist Forest Products Commission). Pre dawn water potentials were taken in 2004 (Ian Dumbrell 2008, Research scientist Forest Products Commission pers. comm.) as part of the assessment of water use of *P. pinaster* Aiton on the Gngangara Mound.

The results from these previously unpublished pre drawn water potential studies are shown in Figure 14. Three sites for this study were chosen:-

- One Site in Gngangara plantation planted in 1955 with less than 5 metres depth to water table and an LAI at time of measurement in 2004 of  $1.1 \text{ m}^2/\text{m}^2$ ,
- Two sites in Pinjar plantation planted in 1977 with depth to water table greater than 20 metres and with an LAI at time of measurement in 2004 of  $2.4 \text{ m}^2/\text{m}^2$ .

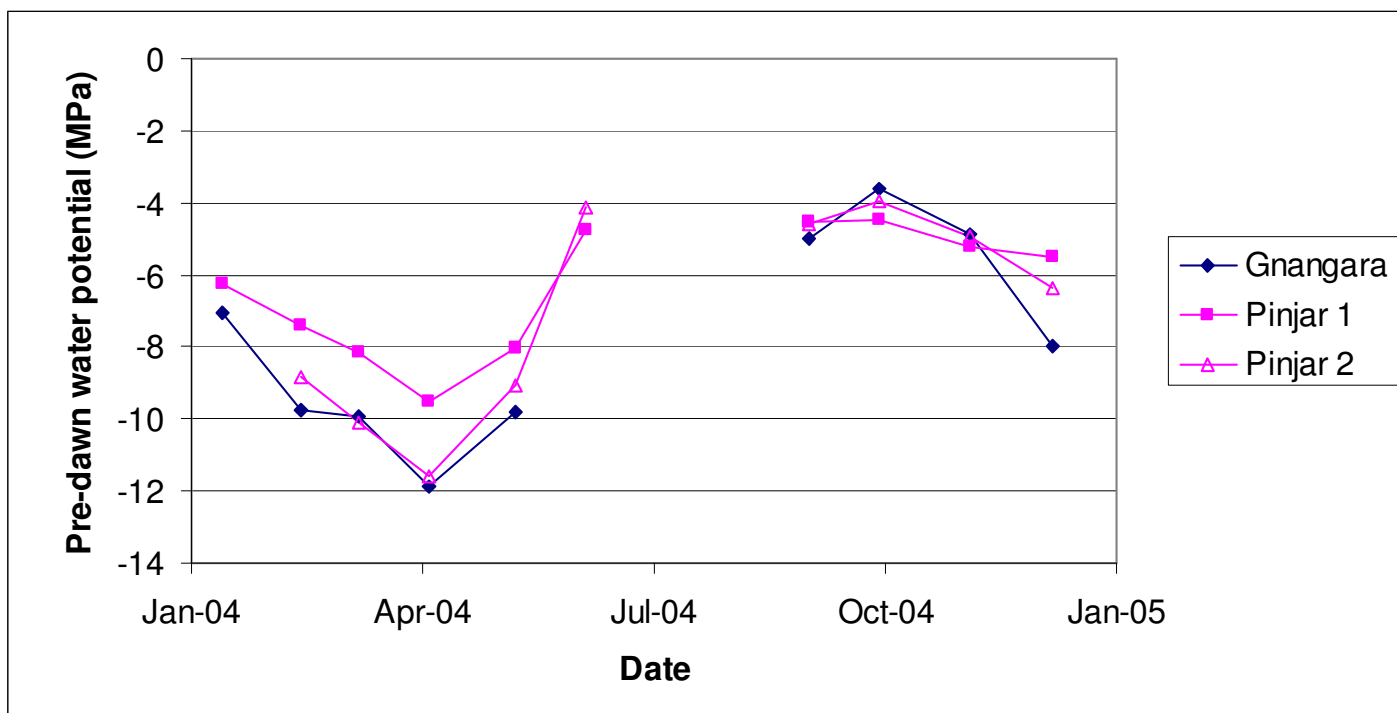


Figure 14. Results from DU276 Gngangara and Pinjar predawn water potentials

The Gngangara site has similar predawn water potentials to the Pinjar 2 site but lower than the Pinjar 1 site. Indicating it is under more water stress than the Pinjar 1 site and similar water stress to the Pinjar 2 site. The Gngangara site had less than half the leaf area of the Pinjar sites at the time of measurement. Given this, the Gngangara site would be expected to have greater water availability as it would have less water demand because of its lower LAI. It should then have higher pre water dawn potential and hence less water stress. In addition the Gngangara site is significantly shallower to the water table and if the theory that it was using ground water was correct it should also have a higher pre water dawn potential and hence less water stress. However, the water potential studies indicate that this is not the case. Trees growing on the Gngangara site do not have less water stress.

These observations indicate that the trees on the Gngangara site are not accessing the groundwater table. The relatively greater stress for unit leaf area at Gngangara also indicates that there is less water available at sites with shallow water tables. This concurs with Butcher

(1977) who concluded that water uptake is restricted to the unsaturated zone of the soil profile because the saturated watertable is limiting root growth. It can be hypothesised that it is the difference in unsaturated soil depths that account for the difference in water stress between sites.

The 1978 plantings in Pinjar plantation extend over different depths to the water table. The stands along Aqua Road (Figure 15) all had approx 650 stems/ha in 2000 and had received identical silvicultural treatment. Investigation of the satellite derived LAI for these stands showed that on stands growing on sites with shallow water tables there was a lower LAI ( $2.6 \text{ m}^2/\text{m}^2$ ) prior to the thinning in 2001 than the areas with deeper water tables, which had an LAI of  $3.0 \text{ m}^2/\text{m}^2$  (Table 2).

Table 2. LAI in 2000 at different depth to water table classes for Pinjar plantation 1978 plantings on Aqua Road

Depth to Water table in 2002 (m)	LAI ( $\text{m}^2/\text{m}^2$ ) in 2000
10 to 15	2.6
15 to 20	3.0
20plus	3.0



Table 3. Recorded average height for P1967 in Gngangara from 1997 inventory

Depth to Water table in 2002 (m)	Average ht (m)	95% confidence interval for mean
5 to 10	16.6	0.3
10 to 15	18.2	0.4
15 to 20	20.0	0.4
20plus	20.4	0.1

The evidence from the growth records documented above shows that growth is suppressed on sites with shallow water tables relative to sites with deeper water tables. This is contrary to what would be expected and indicates that the trees on these sites are not accessing the water table. This suggests that it is the volume of the water in the unsaturated zone beneath the trees that is the factor limiting growth. Logically on sites with shallow water tables, there is less total water in the unsaturated soil profile and this factor appears to account for the difference in growth between sites.

#### **viii) Summary of growth and water usage of Gngangara Mound *P. pinaster* Aiton**

The growth data (Butcher 1977, Hopkins and Butcher 1999a and Hopkins and Butcher 1999b) on *P. pinaster* Aiton demonstrates that this species comply to the “Moller Plateau” principle when grown in the climatic and soil conditions of Gngangara Mound. The growth data also shows that it is possible to thin *P. pinaster* Aiton to a range of densities without reducing stand increment. The soil moisture studies by Butcher (1977) show that available water is a major limiting factor in tree growth that can be partially compensated by thinning. This means that thinning can be used to reduce water usage so that it is less limiting on individual trees and then only limited stand growth is lost.

Growth rates of *P. pinaster* Aiton on Gngangara Mound correlated with rainfall and where there is a decline in rainfall there is a corresponding decline in tree growth

The key points that can be summarised about the evidence on the relationship between growth rates and water table depth on the Gnangara Mound are:-

- Contrary to what would be expected, growth on sites with shallow water tables is less than on sites with deep water tables.
- This indicates that the trees on these sites are not accessing the water table.
- This suggests it is the volume of the water in the unsaturated zone beneath the trees that is the factor limiting growth not the depth of the water table.



## 5. Leaf area index of Gnangara Mound *Pinus pinaster*

### Aiton

#### i) Introduction

The Vertical Flux Model for the Perth region was designed by CSIRO Land and Water to calculate recharge to the coastal aquifers of the Gnangara Mound (Barr, Xu and Silberstien 2003).

The LAI of perennial vegetation is required to estimate recharge rates under both the native vegetation, primarily *Banksia sp.* woodland and the pine (*P. pinaster* Aiton) plantations within the model domain of the Vertical Flux Model for the Perth region (Hodgson 2002).

Land cover (which is measured by LAI) is a major component of the water balance determining the classification of recharge response units in the model (Hodgson 2002).

Consequently an understanding of the site specific LAI dynamics is an essential prerequisite for the use of the model developed for tree volume increments and water outcomes of *Pinus pinaster* Aiton plantations on the Gnangara Water Mound. In this study, LAI was used to assist in the analysis of the potential to optimise water recharge and timber production from *Pinus pinaster* Aiton plantations on the Gnangara Water Mound.

The overarching research question is:-

- Is there a pattern to Leaf Area Index (LAI) of *Pinus pinaster* Aiton on Gnangara Mound and if so what is it and what explains the pattern?

The question can be further subdivided into the following: -

- Is a maximum LAI reached and what is it for the site?
- How does LAI grow from planting to first thinning?
- How does LAI respond to thinning? (At what rate does it regrow back to maximum?)

- How does maximum LAI and rebound after thinning respond to other factors such as depth to water table, low stand stockings, stand age and drought?

## **ii) Methodology.**

The purpose of the LAI component of this study was to be descriptive and to define the behaviour of LAI accurately over time for the plantation. Once it was described, explanatory research to explain why it behaves, the way it does was undertaken. Since understanding of LAI is seen as important to assist in making water outcome decisions, waiting for results from a long-term study is unacceptable. Consequently, a sequence of historical satellite photography was used to reconstruct the apparent pattern of LAI growth over time.

The need to understand how LAI changes over time is a form of longitudinal study. That is, the study is of the same population over time. The sequence of satellite photography allowed a tracking of the changes after an event such as thinning and aging over time.

It is also essential to derive a specific relationship because: -

- 1) Dean and Baldwin (1996) point to each LAI study needing to be done for a specific species on a specific site as the results of both other species studies and studies from different places cannot be generalized as there are different mediating variables operating.
- 2) The Gngangara Mound's hydrogeology is also unique and does not fit the pattern found elsewhere in Australia (Vertessy, Silberstein and Hatton. 1999). This could have a significant impact on LAI development.

Hence, a specific study of Gngangara was required to understand and explain it and the specific results may not be applicable to other systems. However, the techniques used elsewhere to study LAI such as remote sensing are relevant.

### **iii) Use of satellite remote sensing at Gnangara Mound for *P. pinaster* Aiton LAI**

Land Monitor is a project which involves both state agencies from Western Australian and Commonwealth agencies which was established in 2000 to systematically monitor and predict salt-affected land, and monitor the condition of both remnant and revegetated areas, over an 18 million ha area. It used Landsat scenes that are available every 16 days from 1987 onwards, which can be accessed from archived collections (Land Monitor 2003). Each image covers a swath 185 kilometres wide and has a maximum resolution of 30 metres.

From these, a sequence of calibrated satellite imagery has been produced by the Land Monitor project (Allen and Beetson 1999). Being calibrated allows a direct comparison between years and makes this set suitable for time series analysis projects. It is produced from seven summer dates of calibrated TM data, at approximately 2-yearly intervals from 1988-2003 and then yearly summer dates from 2003 to 2007.

#### **a) Satellite image calibration**

For any series of satellite images to be useful they need to be calibrated to one another and correctly positioned with regard to a common map base (Caccetta, Allan and Watson 2000).

The Land Monitor series of photos undergoes calibration in two ways (Land Monitor 2003): -

- 1) Co-register the sequence of images to a common map base. This is done to ensure each year's data is at exactly the same place on each map.
- 2) Calibrate the images to a common radiometric base so that the numerical values through time may be compared. The Land Monitor summer 1994 photo has been used as the base for this.

A new technique, which was different to the calibration carried out previously, was introduced in 2003. It caused a decrease in the reported values of LAI by 20%. Analysis in

2004 has pointed to this change being caused mostly by the difference in underlying photo calibration (Jeremy Wallace CSIRO 2004 pers. comm.). This issue appears resolvable but it is important to avoid this source of potential variation in future studies. For the purposes of this study all the images used for LAI determination are calibrated exactly the same to avoid variation such as those described above.

#### b) Development of a calibration for the satellite images for LAI

It is difficult to destructively sample enough trees to ensure a representative sample because of all the mediating variables. Commonly a few destructive samples are taken and these are then bulked out with the use of an optical device such as a Licor to obtain LAI (Cammaraat et. al. 2001). Studies by CSIRO on Gngangara used this technique (Hodgson 2003). This method has been described in a number of studies including Chen, Vierling and Conley (2003), Hall et. al. (2003) and Scurlock, Asner, and Gower (2001).

In developing the allometric relationship between stem diameter, tree leaf area and remote sensing data for *P. pinaster* Aiton at Gngangara Mound the CSIRO project team used a Licor instrument to measure the LAI of their plots (Hodgson 2003). The summary of the techniques they used is that within the boundaries of a single pixel area from satellite photography several trees were destructively sampled for leaf area and breast height diameter. These samples were used to calibrate the LAI values derived from the satellite photography.

Smolander and Stenberg (1996) warn that Licor measurement of LAI can have a non-linear relationship to a direct measure of LAI when the relevant proportions of LAI branch area and stem area change. Smolander and Stenberg (1996) identified that the amount of branch and stem area needs to be included in older stands so that models of the relationship provide correct results. The variation in age and hence woody area in the crown must be recorded to understand how the relationship changes with increasing age and the woody area of the stem.

Rautiainen et. al. (2003) states “in all model applications, errors in image processing and plot location within a pixel (i.e., whether the plot centre is close to the pixel centre or the pixel border) should be considered” (p. 322). In the case of the Licor instrument used by CSIRO, there is the possibility of discrepancy between plot size (field of view of the instrument) and Landsat image resolution. To minimise such an error two measurements were taken from opposing sides of each of the plots to calculate the average LAI.

c) Summary of method used by CSIRO project team (Hodgson 2003)

The methodology used was: -

- Destructively sample three or four representative trees and develop a relationship between diameter and leaf area.
- Use an optical device (Licor) to measure a leaf area index value for a plot.
- Measure the diameters of each tree in the plot.
- Use the diameter to leaf area relationship developed to calibrate the Licor readings for *P. pinaster* Aiton on the Gngangara Mound from these plots.
- Record Licor readings across the Gngangara Mound to capture the range of LAI values present.
- Use the calibrated Licor derived LAI values to calibrate the satellite photography.

This procedure by its nature embeds a series of variables at each calibration stage. It therefore becomes more difficult to give a confidence range for the final derived satellite LAI value. However, comparisons by Hodgson (2003) have shown correlation coefficient of 92% for normalised difference vegetation index (NDVI) to LAI from Licor consequently there is a high degree of accuracy possible between the optical sample values and those derived by satellite. Mapped results for 1988 and 2002 are shown at Figure 16.

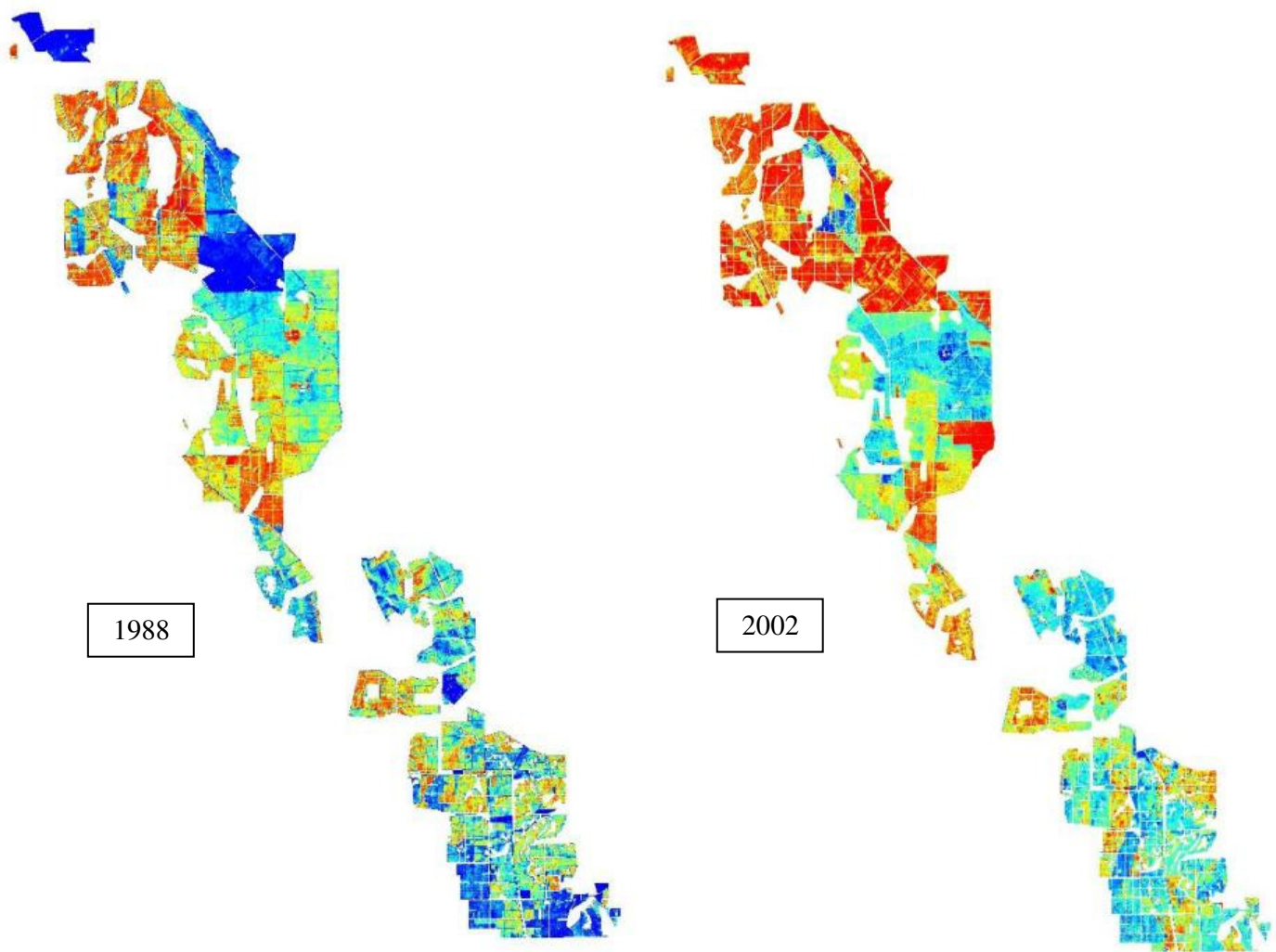


Figure 16. Leaf area (LAI) from satellite series Gungahara Mound pine plantations (Same Graded colouring used for 1988 and 2002 where dark blue represents low values through to the dark red high values)

#### iv) Integrating silvicultural information and satellite derived LAI

The time sequence of the available photos from the Land Monitor series allowed LAI values for each stand to be plotted over time. Combining this with silvicultural information, such as time of thinnings, allowed a series of LAI values after thinning to be identified and rebound growth rates of LAI to be calculated. It was also possible to find stands that reach canopy closure during this time. These stands were analysed to determine the maximum LAI value expressed and whether these values reached a plateau or not.

Analysis of stand age, stocking and depth to water table was undertaken to see how these variables interact with the maximum values recorded. Further analysis was carried out to determine how LAI regrows after thinning and how it grows from time of planting.

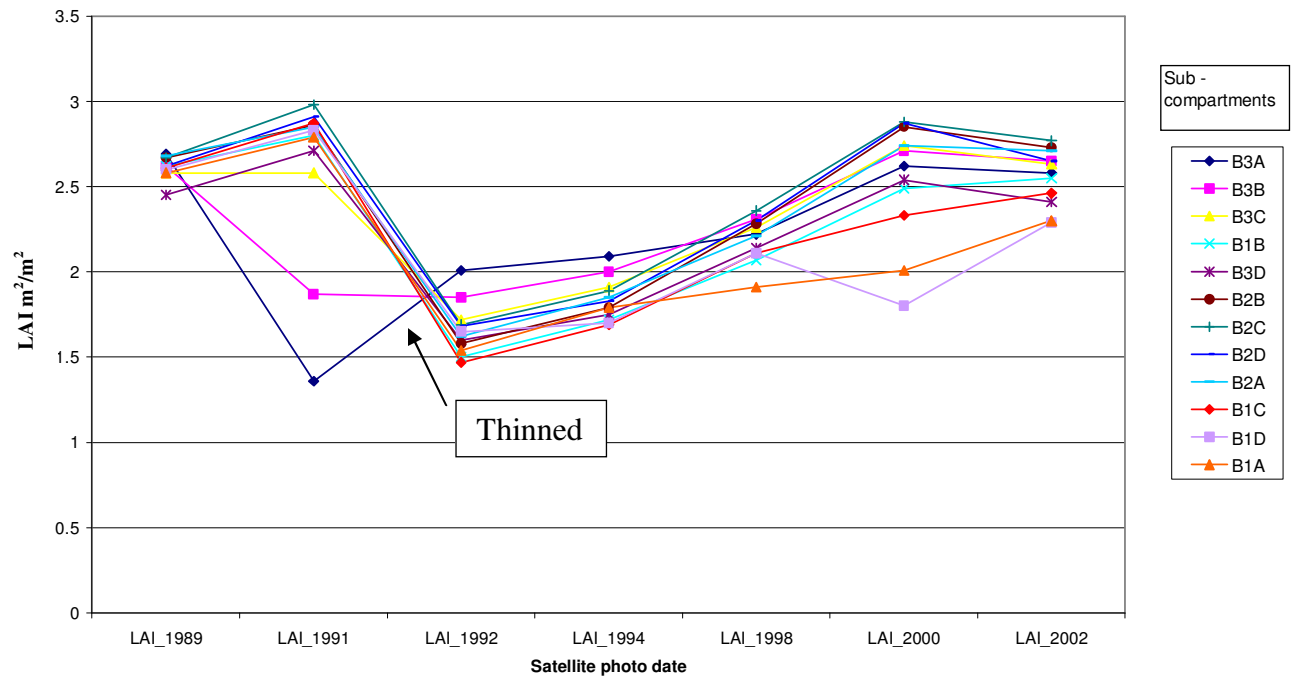


Figure 17. LAI for Pinjar planted 1969, thinning occurred in 1992 (See Figure 84 for location)

The sequence of results from the study is demonstrated in the example shown in Figure 17. It confirms that there is a distinct pattern. In this instance, the stand LAI was at  $3 \text{ m}^2/\text{m}^2$  in 1991. In 1992 thinning removed approx half the trees and the LAI reduced by approximately half down to  $1.5 \text{ m}^2/\text{m}^2$ . Subsequently the LAI regrew to between 2 and  $2.9 \text{ m}^2/\text{m}^2$  by 2000. This establishes that LAI at a point in time for such a stand is the result of the timing of and intensity of silvicultural treatment. Once the relationship between LAI and silvicultural treatment is understood it can be used to described the history of LAI for a stand and predict its future LAI under different silvicultural treatments.

#### **v) Field observations and aerial photography**

Field observational and analysis of air photos was carried out to gain a visual perspective of LAI values. Figures 18, 19, 20, 21 and 22 show examples of the on the ground perspective along with the related satellite derived LAI value.

These field observations were used to visually inspect stands on the ground, to confirm the accuracy of the LAI values being derived from satellite photos. The author was able to quickly gain a reasonably accurate ability to predict LAI values for a stand from direct on ground inspection after using the satellite values as a guide to train his eye.



Figure 18. P77 Pinjar 170 stems/ha LAI 2002  $1.56 \text{ m}^2/\text{m}^2$  photo taken September 2003 (See Figure 84 for location)





Figure 19. P76 Pinjar 470 stems/ha LAI 2002  $2.95 \text{ m}^2/\text{m}^2$  photo taken September 2003 (See Figure 84 for location)



Figure 20. P78 Pinjar LAI  $1 \text{ m}^2/\text{m}^2$  thinned approx two years earlier photo taken September 2003 (See Figure 84 for location)





Figure 21. P84 Yanchep LAI  $3 \text{ m}^2/\text{m}^2$  photo taken September 2003 (See Figure 85 for location)



Figure 22. P92 Yanchep LAI  $3 \text{ m}^2/\text{m}^2$  photo taken September 2003 (See Figure 85 for location)

A series of orthophotos were overlain with LAI values. On the orthophotos the lighter green areas did correlate to areas of lower LAI and the LAI values could be explained with the aid of silvicultural history in regard to thinning times and intensity (Figure 23). These orthophoto checks also provided further evidence that the values being produced from satellite photography were plausible, as compartments with denser canopies had correspondingly higher LAI.





Thinned 1995/96 to 250 stems/ha approx a roughly 50% reduction probably to LAI of  $1.4 \text{ m}^2/\text{m}^2$  at the time Regrown to 2 since then

Thinned 1999/2000 probably to an LAI of approx  $1 \text{ m}^2/\text{m}^2$  due to a 64% reduction in stocking. It has regrown to  $1.25 \text{ m}^2/\text{m}^2$  since

Figure 23. Airphoto of Pinjar showing LAI values in 2002 from satellite derived Land Monitor series (See Figure 84 for location)

#### vi) LAI at Gngangara Mound for *P. pinaster* Aiton

The whole of Gngangara mound *P. pinaster* Aiton satellite derived LAI areas were plotted over time for 0.25 wide LAI categories (Figure 24). Also the resultant overall average LAI change over time was derived (Table 4). From Figure 24 and Table 4 it can be seen that from 1988 to

1996 average LAI increased with increasing areas moving into the higher LAI classes. The effects of increased (almost double) annual thinning areas carried out post 1996 can also be seen. These reduced significant areas from high LAI (LAI of 3 m<sup>2</sup>/m<sup>2</sup>) to moderate LAI (LAI of 1.5 m<sup>2</sup>/m<sup>2</sup>).

Table 4. Average LAI over time for *P. pinaster* Aiton on Gngangara Mound

Year	1988	1996	1998	2002	Derived 2008
Average LAI m <sup>2</sup> /m <sup>2</sup>	1.23	1.99	1.58	1.78	1.57

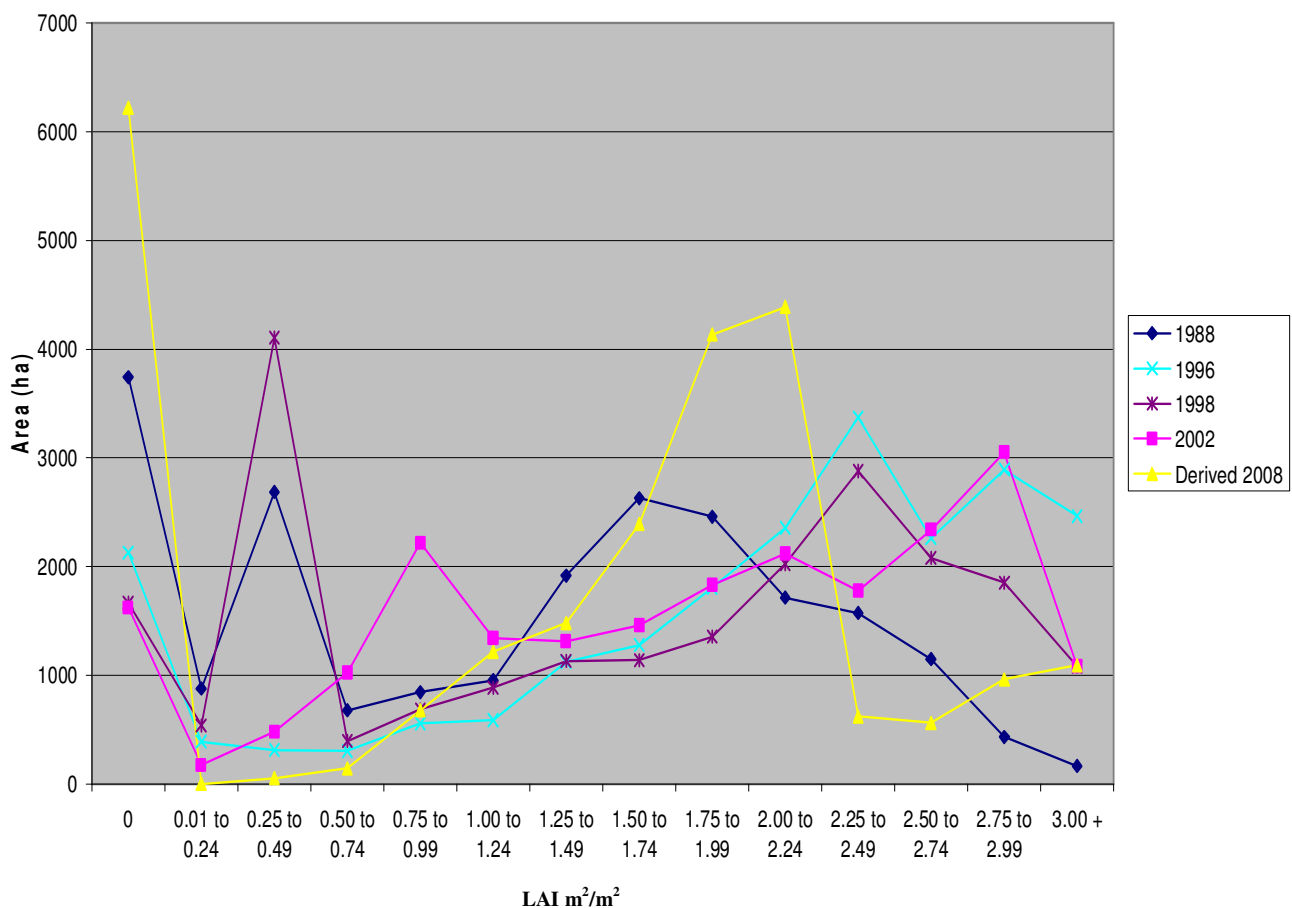


Figure 24. *P. pinaster* Aiton LAI by class over time at Gngangara Mound

Investigation into the relationship of LAI to just basal area alone, stocking alone and age alone was carried out (Figures 25, 26 and 27). There was no relationship between plots of LAI from 2002 against basal area, age and stocking. Plots failed to find any pattern in LAI values directly attributable to these factors alone.

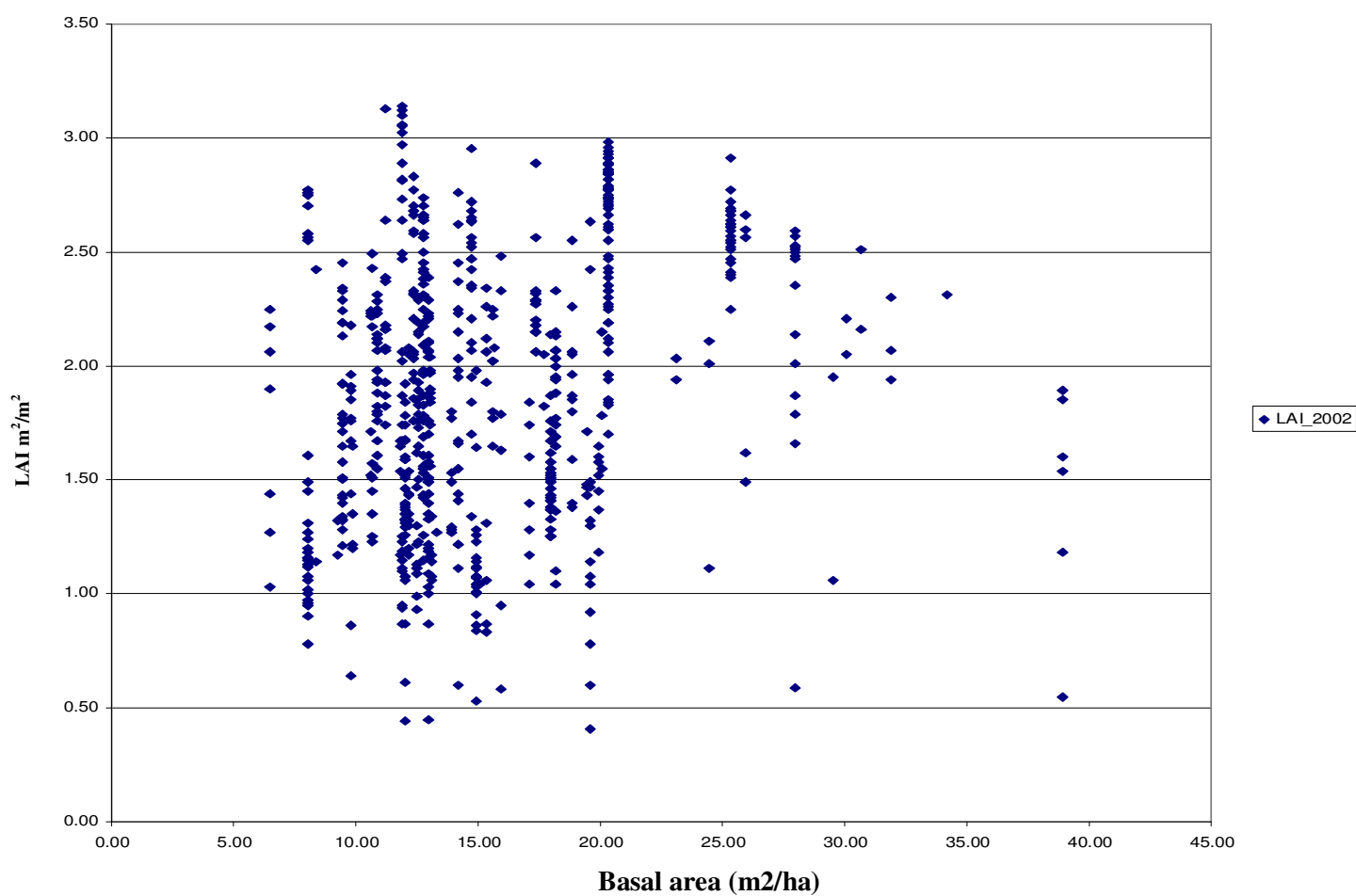


Figure 25. Plot of Basal area against LAI in 2002

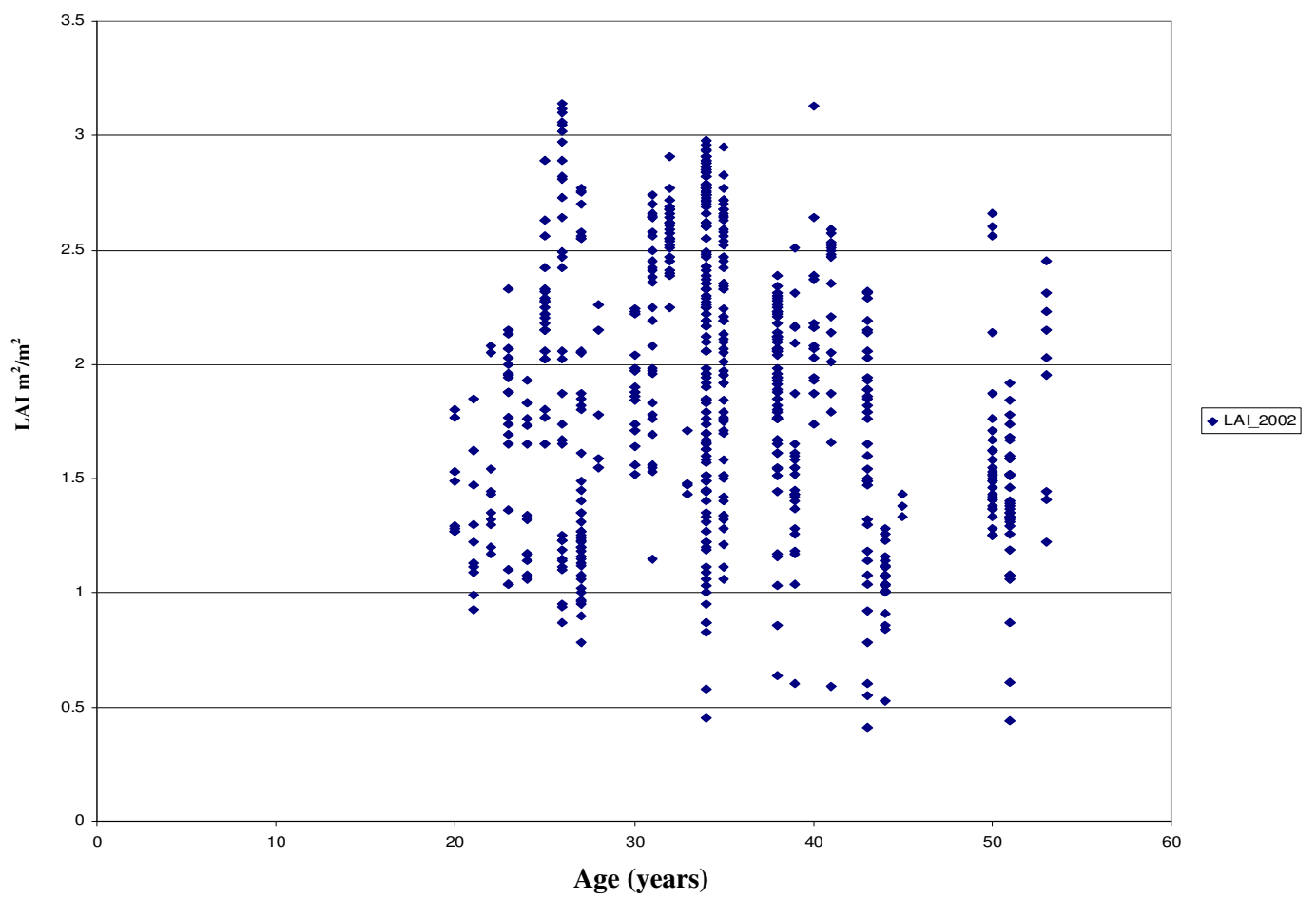


Figure 26. Plot of Stand age against LAI in 2002

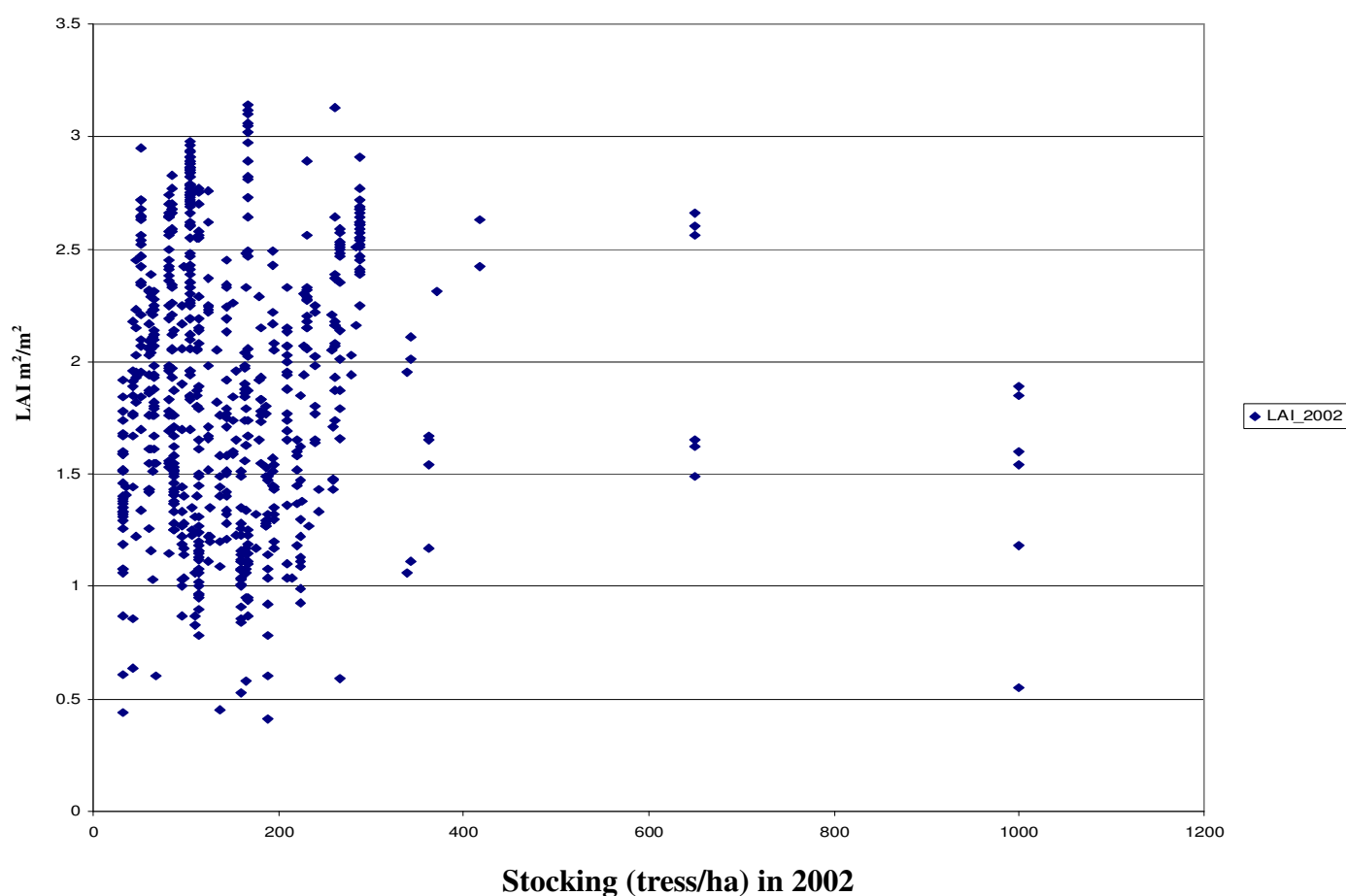


Figure 27. Plot of Stocking against LAI in 2002

#### vii) Maximum LAI at Gngangara Mound for *P. pinaster* Aiton

Due to the size of the satellite image pixel there is a significant likelihood that edge effects will give a false LAI reading for individual areas of pine that are very small (less than 2 hectares). These very small areas (less than 2 hectares) were therefore excluded from all the following analyses to avoid likely false LAI readings.

There is a trend of gradual reduction of maximum achievable LAI for areas that are below approximately 150 stems/ha and a rapid reduction in LAI from below 50 stems/ha (Figure 28). When LAI is plotted against age (Figure 29) stands below 9 years of age are consistently



below the maximum achieved by older stands. This can be explained as they would be unable to have fully occupied the site by that age, as they have not grown sufficiently to be able to do so. There is also trend of declining LAI after approximately age 35 years of age. This may however be reflecting the much lower stocking rates and hence slower overall stand regrowth rates of LAI due to both age and lower stocking levels. Some of the stands above age 35 if given enough time may be able to recover to the site maximum. The stands shown in Figure 28 and 29 indicate that the site maximum is approximately LAI  $3.3 \text{ m}^2/\text{m}^2$ .

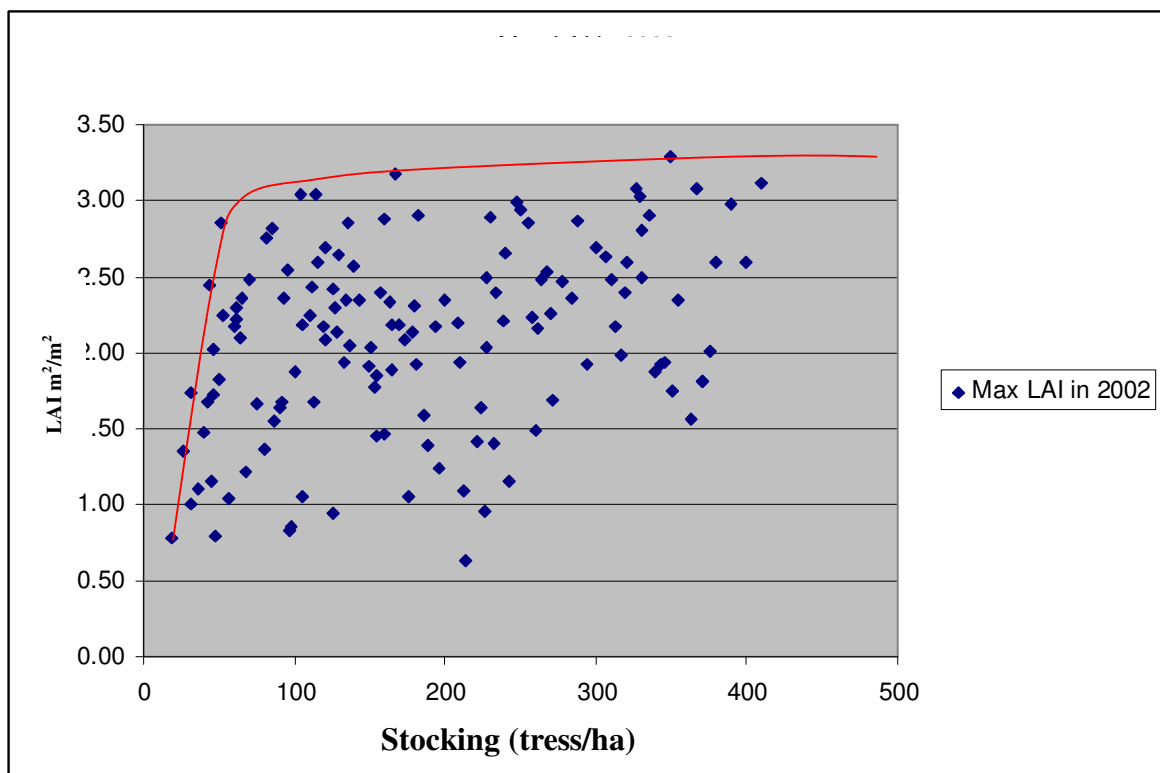


Figure 28. Maximum LAI in 2002 for a range of stockings

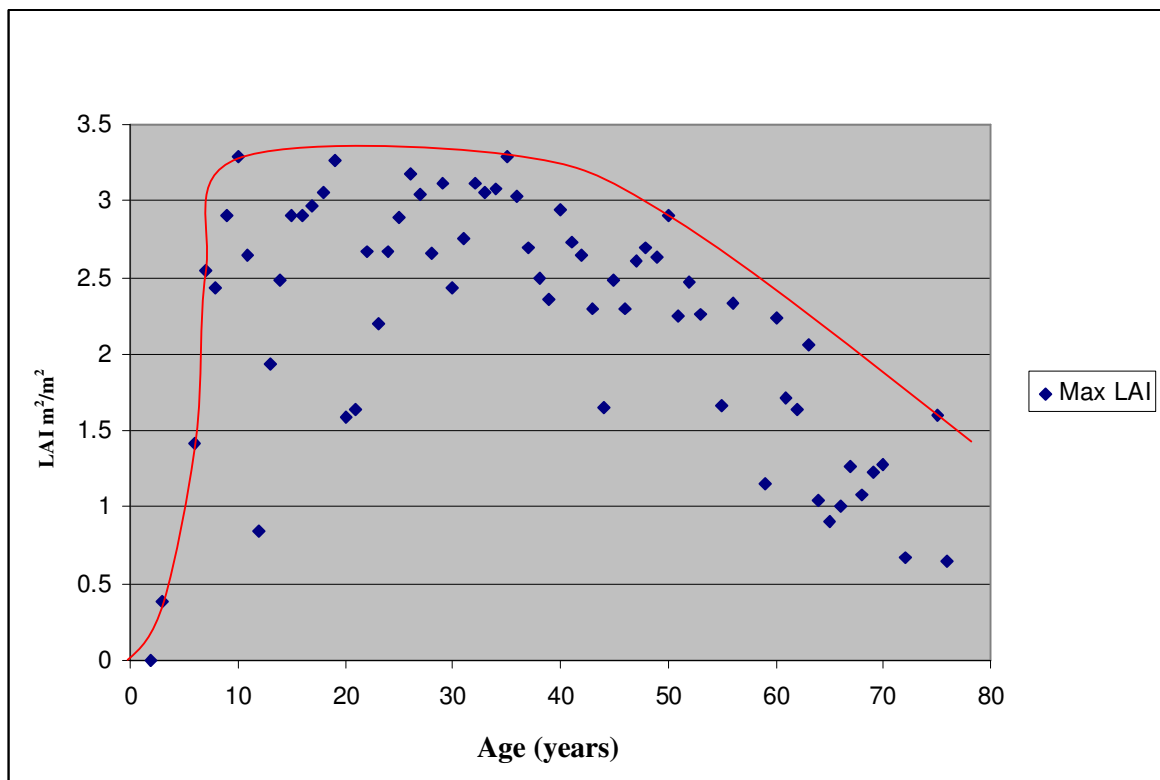


Figure 29. Maximum LAI in 2002 from a range of ages

Further investigation was undertaken to find a site of high basal area and check the maximum LAI values. P53 Gngangara stand 9F1 (Figure 30, 31, 32 and 33) was chosen for investigation in detail because it had the highest recorded basal area from the 1997 inventories at 57 m² BA and 870 stems/ha in 1997. Being at high basal area it should have theoretically obtained site maximum LAI of 3.3 m²/m². It however had only a LAI of approx 2.3 m²/m² and had been at that level since 1988 (Figure 30).

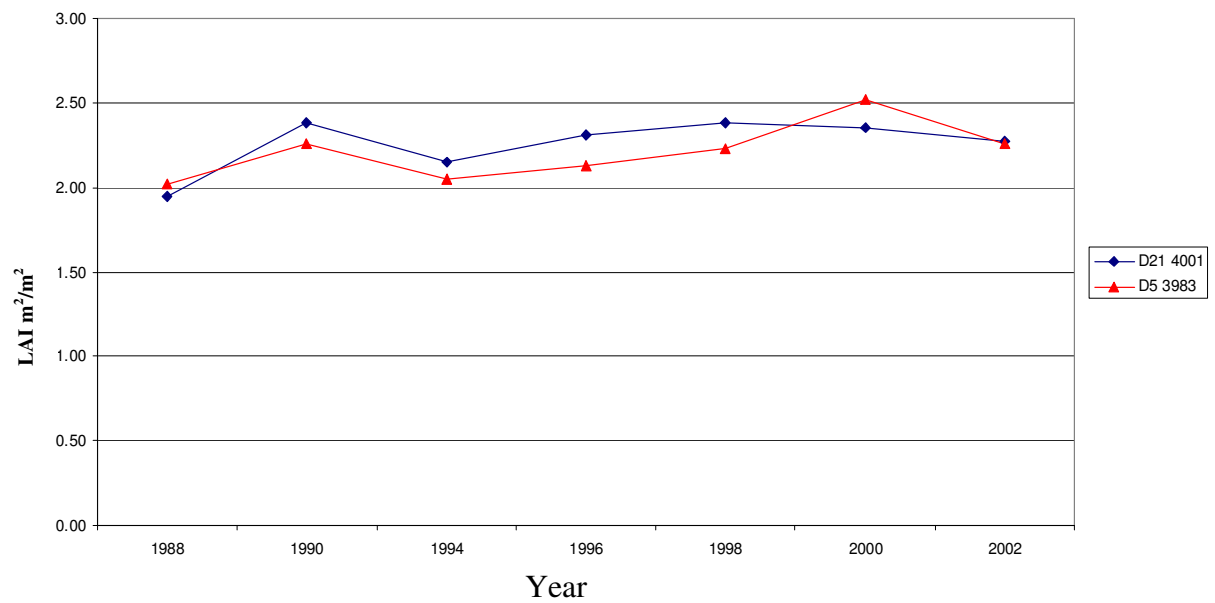


Figure 30. LAI over time for P53 Gngara Stand 9F1 inventory sub-stands D21 and D5

The failure of this stand to reach the site maximum LAI demonstrates that it is not possible to accurately predict LAI only from basal area. This also demonstrates that a more complex relationship exists and further analysis will be required. Consequently, it was decided to investigate the annual LAI growth that occurred after thinning.



Figure 31. P53 Gngangara Stand 9F1 870stems/ha 57 m<sup>2</sup> BA in 1997 LAI 2002 2.27 m<sup>2</sup>/m<sup>2</sup>



Figure 32. January 1999 orthophoto with LAI values for P53 Gngangara Stand 9F1

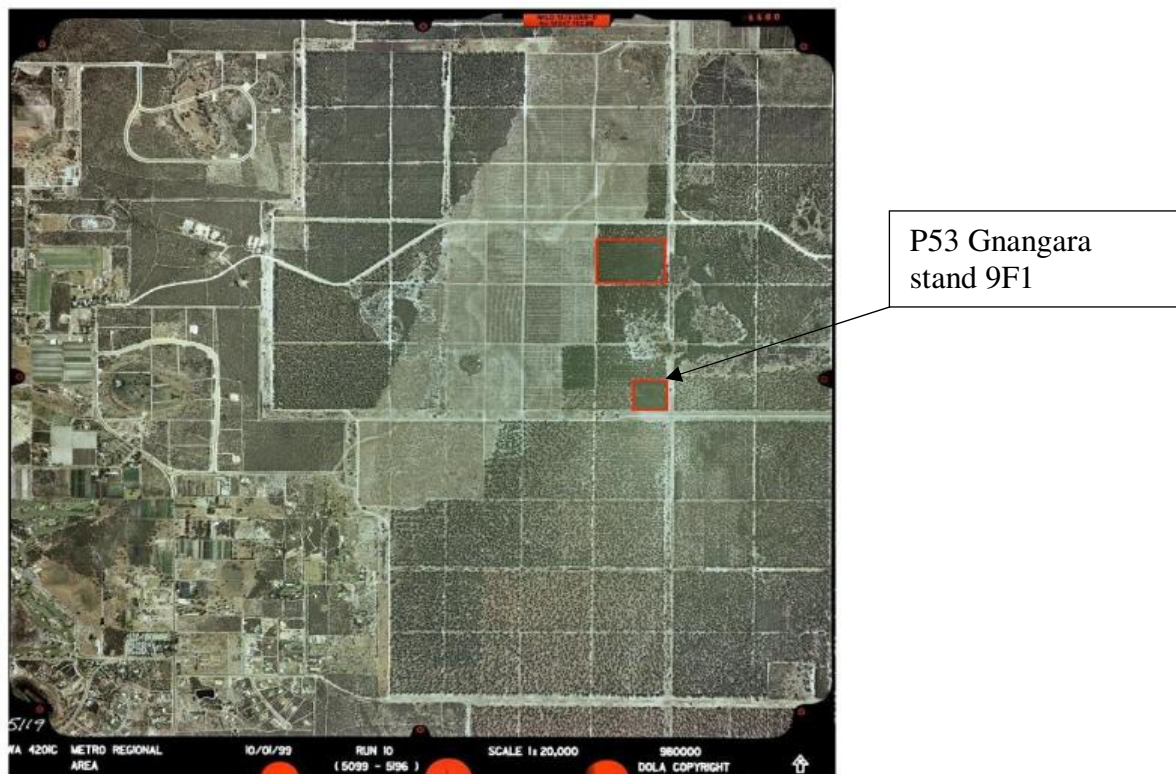


Figure 33. P53 Gngangara stand 9F1 Jan 1999

#### viii) Annual LAI growth at Gngangara Mound for *P. pinaster* Aiton

A analysis data for both silvicultural treatment for the timing of thinning and LAI values to calculate LAI growth post thinning by the stands to reoccupy the site, regrowth of LAI resulted in a data set that was used to analyse the effects of stocking (Figure 34) and age (Figure 35) upon LAI regrowth

There is a strong linear relationship with stocking ( $R^2$  77%) and a weaker ( $R^2$  56%) but still significant negative power relationship with age.



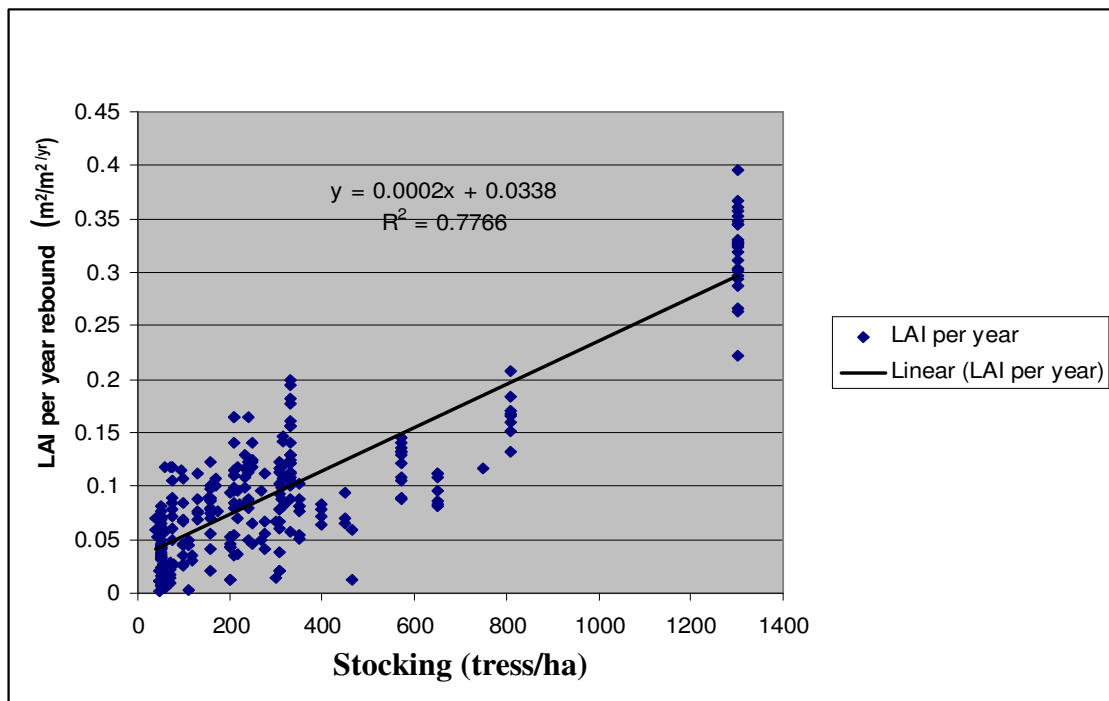


Figure 34. LAI regrowth after thinning vs stocking

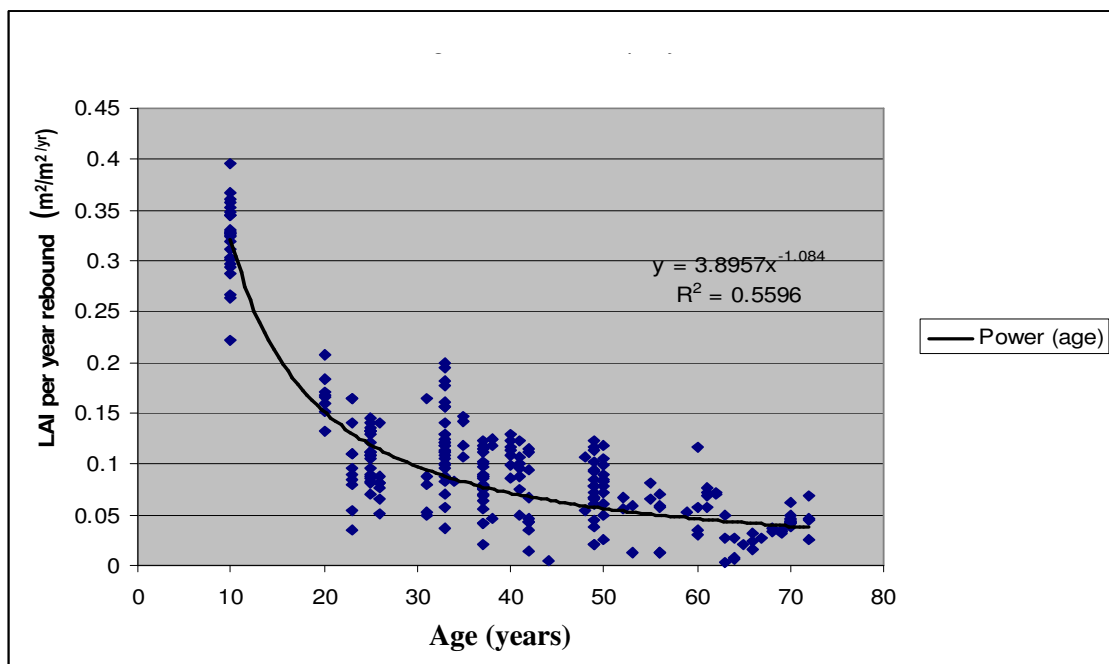


Figure 35. LAI regrowth after thinning vs age

To further understand the impact of both stocking and age a plot of LAI regrowth across multiple ages and stocking level classes was undertaken (Figure 36).

Two patterns emerged. Firstly a decreasing capacity per tree as it ages to regrow in leaf area for the same stocking level and secondly an increasing capacity to regrow leaf area with decreasing stocking for the same age.

At reduced stockings there is more area and soil available and hence water per tree. With increasing age the canopy width of an individual tree reaches a mechanical limit to the amount of leaf and branch it can support. There also appears to be an exponential increase in annual leaf area growth for an individual tree below approximately 250 stems per hectare and a plateau of growth per tree for stockings above approximately 400 stems per hectare.

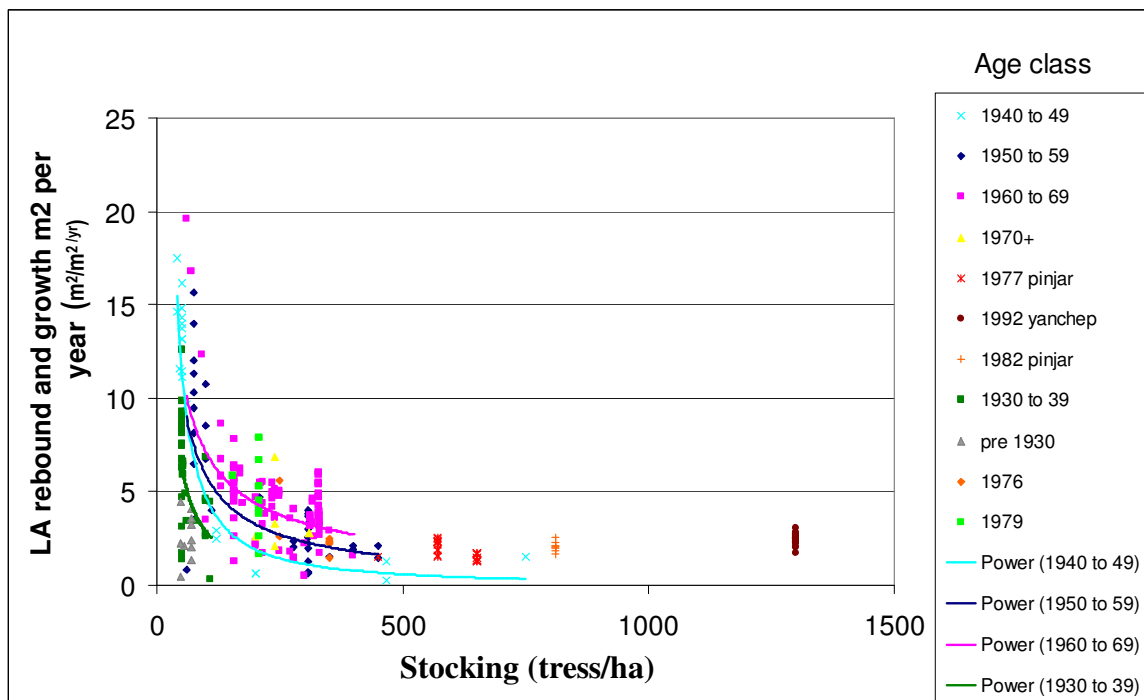


Figure 36. Leaf area per tree rebound after thinning for different ages

It was felt that given the result that both stocking and age had impacts on LAI regrowth and that an additional analysis of combining both data into a 3D surface model could help explain more of the variation than either variable alone

Further analysis was carried out to provide a regression using a paraboloid three-dimensional model (Figure 37 and Table 5) for LAI regrowth after thinning for a whole stand. A two dimensional representation of this relationship is shown in Figure 38. This gave a correlation coefficient of  $R^2 = 0.8333$ , with parameters

z0	5.50E-02
a	-7.74E-05
b	2.58E-03
c	2.08E-07
d	-4.37E-05

where  $\text{LAI regrowth} = z0 + a(\text{SPH}) + b(\text{AGE}) + c(\text{SPH} * \text{SPH}) + d(\text{AGE} * \text{AGE})$ .

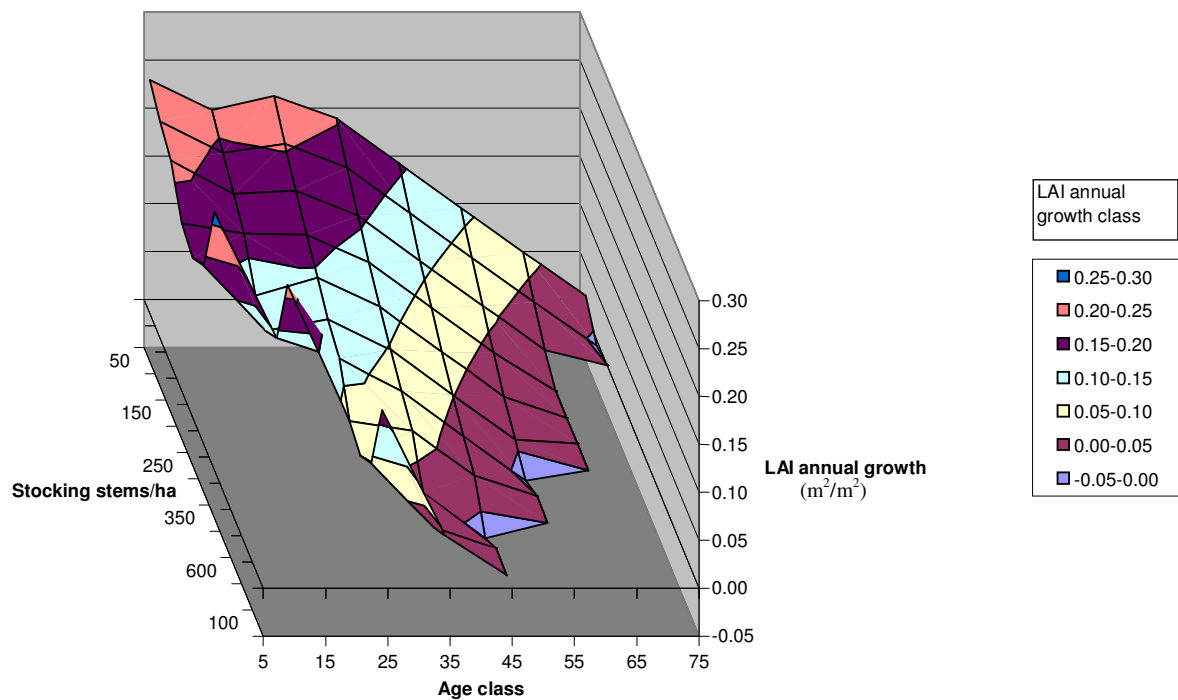


Figure 37. Regression using a paraboloid three-dimensional model



Table 5. Table of Regression using a paraboloid three-dimensional model

LAI annual growth (m <sup>2</sup> /m <sup>2</sup> )	Age Class							
	5	15	25	35	45	55	65	75
50				0.20	0.16	0.11	0.06	0.02
100			0.23	0.18	0.13	0.08	0.04	-0.01
150			0.20	0.16	0.11	0.06	0.02	
200			0.18	0.13	0.09	0.04		
250		0.21	0.16	0.12	0.07	0.02		
300	0.24	0.19	0.15	0.10	0.05	0.00		
350	0.23	0.18	0.13	0.08	0.04	-0.01		
400	0.21	0.16	0.12	0.07	0.02			
600	0.18	0.13	0.08	0.03	-0.02			
800	0.17	0.12	0.07	0.02				
1000	0.19	0.14	0.09	0.04				
1300	0.27	0.22	0.17	0.12				

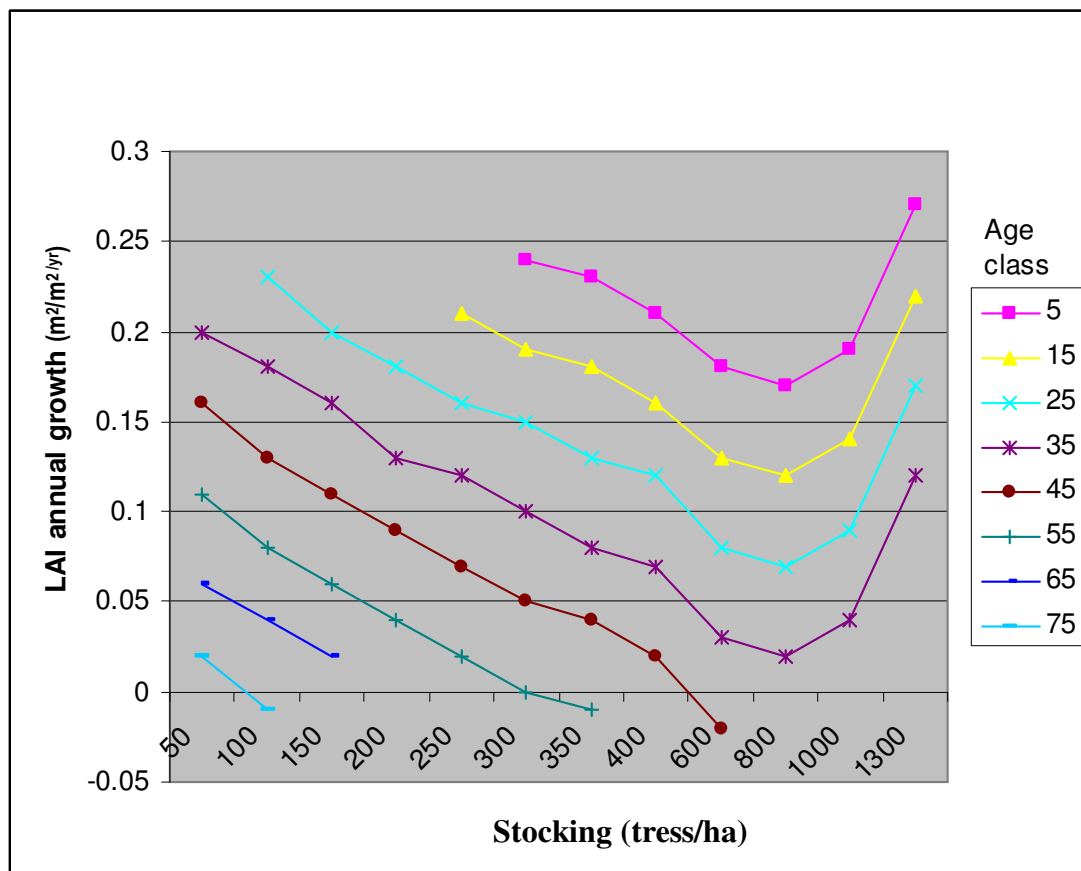


Figure 38. Two dimensional representation of regression analysis results for LAI annual growth

The predicted growth for very old stands, (those greater than 75 years old) with low stockings is negative (Figure 39). These very old stands according to the formula would be shedding total leaf area rather than growing additional leaf area.

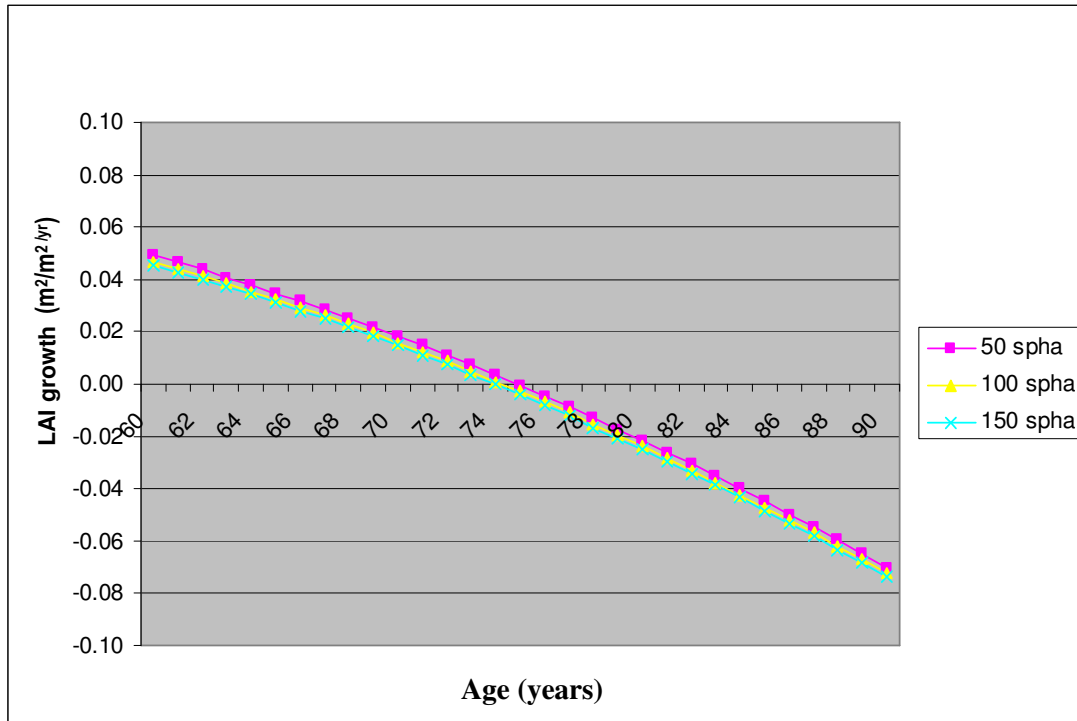


Figure 39. Investigation of impact of very old age on LAI growth prediction

The formula predicts that young stands below 20 years old will have a rapid increasing rate of growth for stockings higher than 1000 stems/ha (Figure 40). This is unrealistic because canopy closure is not reached so quickly, for example LAI at age 3  $\text{m}^2/\text{m}^2$  in stands of 2200 stems/ha from field observations is well short of  $3.3 \text{ m}^2/\text{m}^2$ . There were few stands that had been thinned at very high stockings greater than 1000 stems/ha in the database on which the formula was based. Consequently, it was considered a separate analysis of LAI growth for stands below age 20 was required.

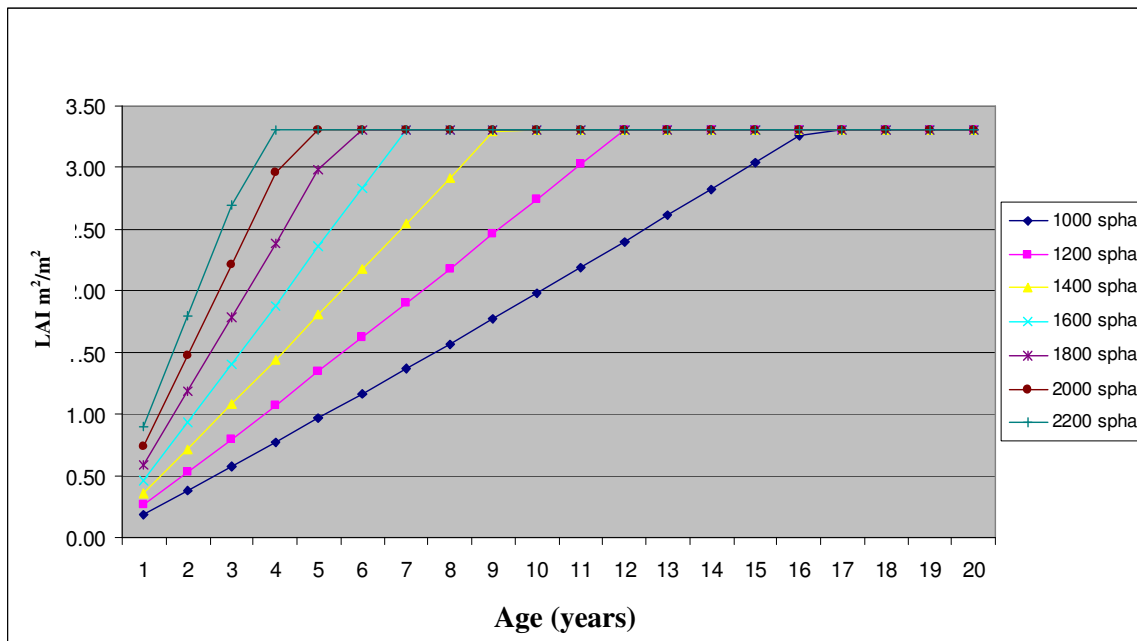


Figure 40. Investigation of LAI annual growth prediction for young stands

#### ix) Young (less than 20 years old ) LAI growth prior to thinning for *P. pinaster* Aiton at Gngangara Mound

A separate investigation of the relationship between of satellite derived LAI for the early growth before age 20 and before first thinning was required to ensure the equation of LAI growth could be relied upon at stockings above 1000 stems/ha. Stands that had not had a thinning and LAI data available from the time sequence where chosen

In order to compare across different planting years the results of early LAI were converted into an equivalent stand age. The resulting curve was sigmoidal (Figure 41).

A sigmoidal curve with  $LAI = 3/(1-81^{((3.5+12/2-age)/12)})$  fits the data with a correlation coefficient of 84.4% (Figure 42). This means that at 3.5 years approximately 10% of the maximum LAI for the site is achieved. This is then followed by 12 years of fast growth at the end of which the stands have reached approx 90% of maximum LAI and LAI growth will then start to reduce growth.

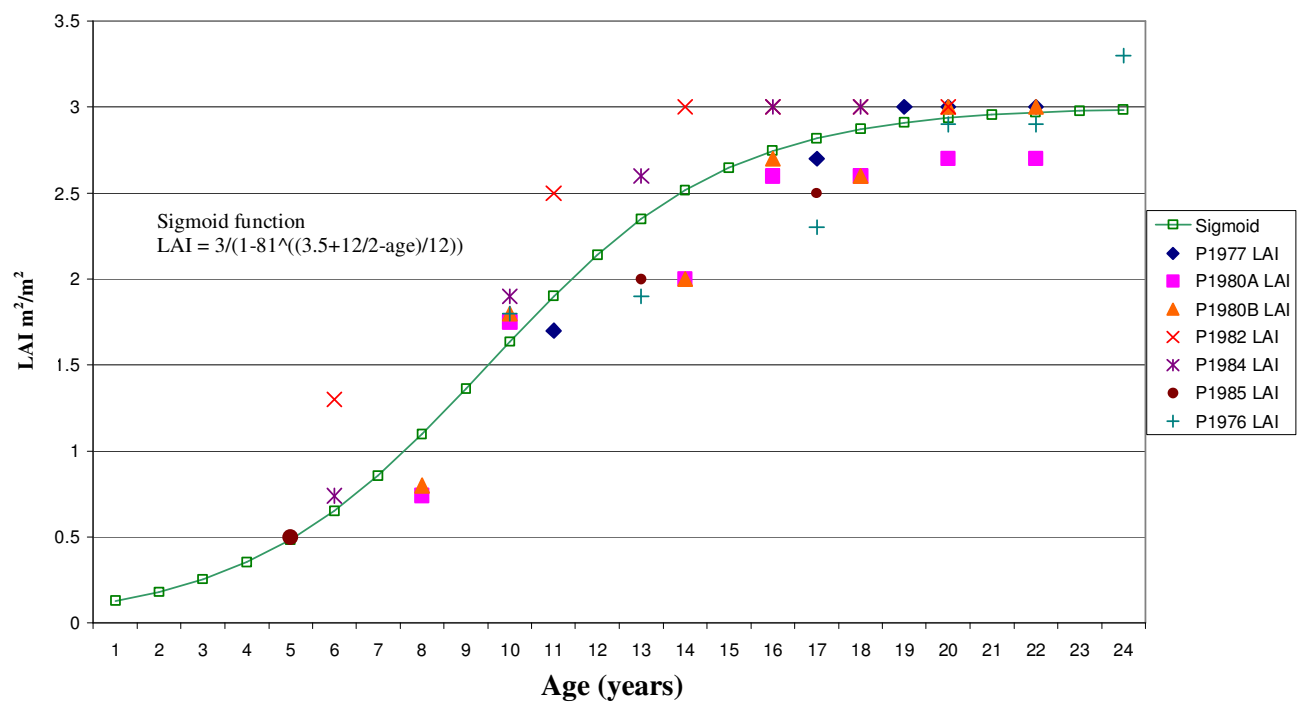


Figure 41. LAI growth from planting until 24 years assuming no thinning was carried out

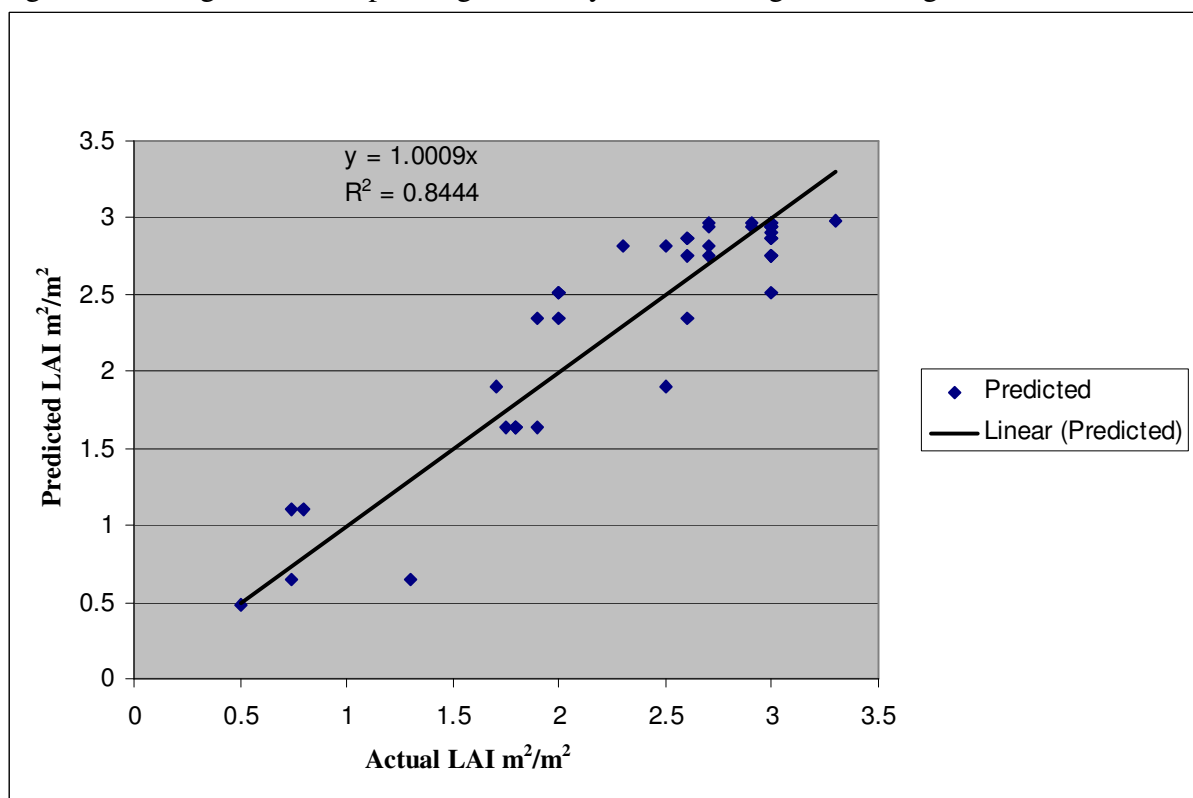


Figure 42. Correlation between actual LAI and predicted LAI from sigmoidal equation

This sigmoidal equation was then compared to actual LAI and the LAI growth predictions across a range of stockings greater than and equal to 1000 stems/ha (Figure 43, 44, 45 and 46).

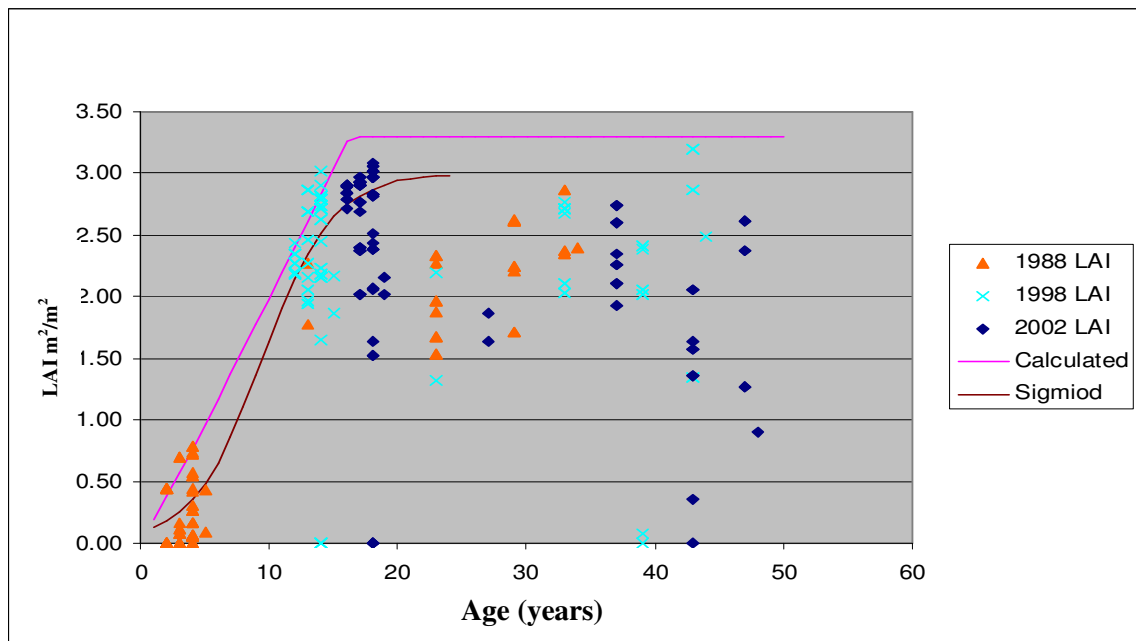


Figure 43. 1000 stems/ha LAI comparison of satellite data, regression analysis and sigmoidal growth pattern

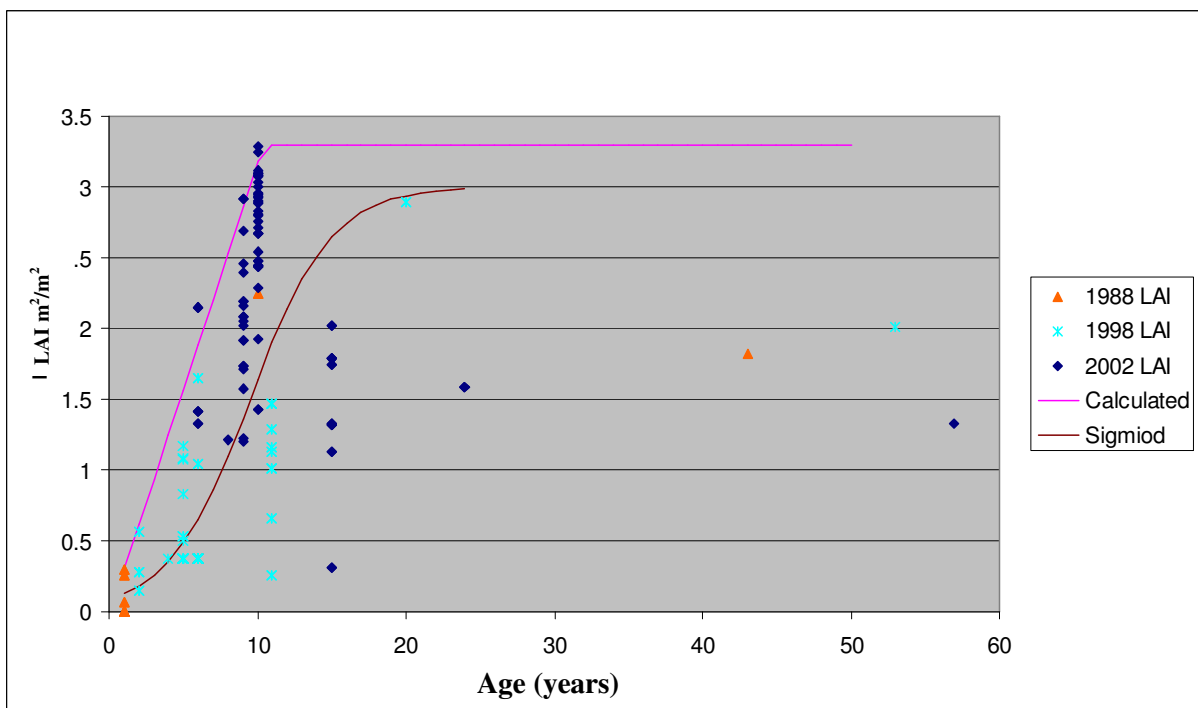


Figure 44. 1300 stems/ha LAI comparison of satellite data, regression analysis and sigmoidal growth pattern

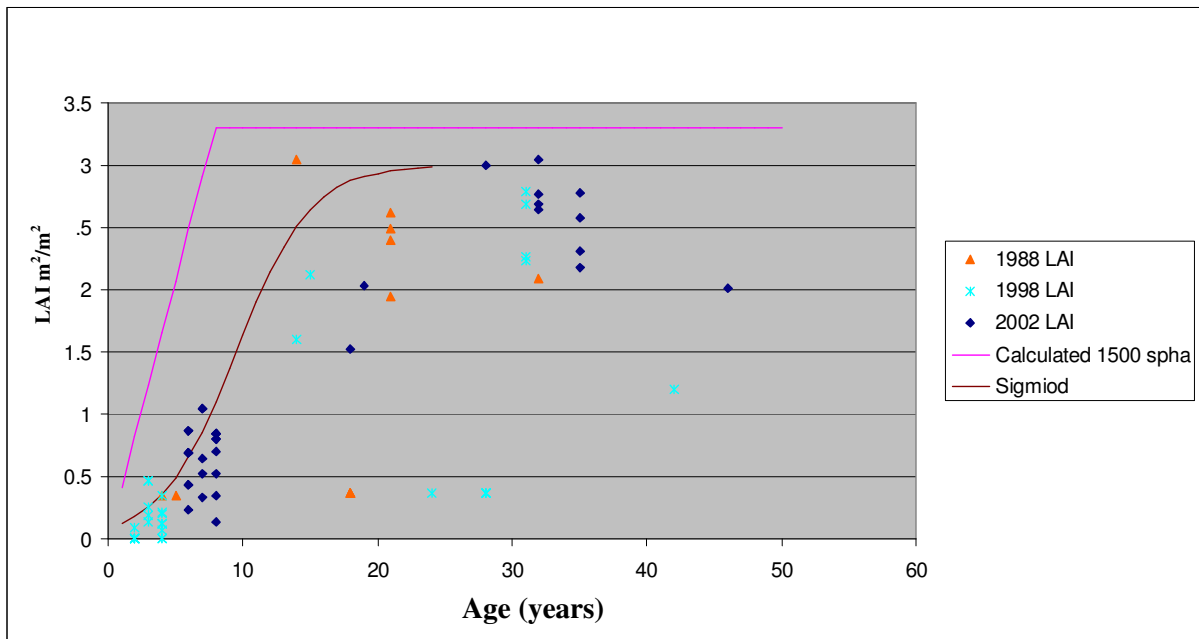


Figure 45. 1500 stems/ha LAI comparison of satellite data, regression analysis and sigmoidal growth pattern

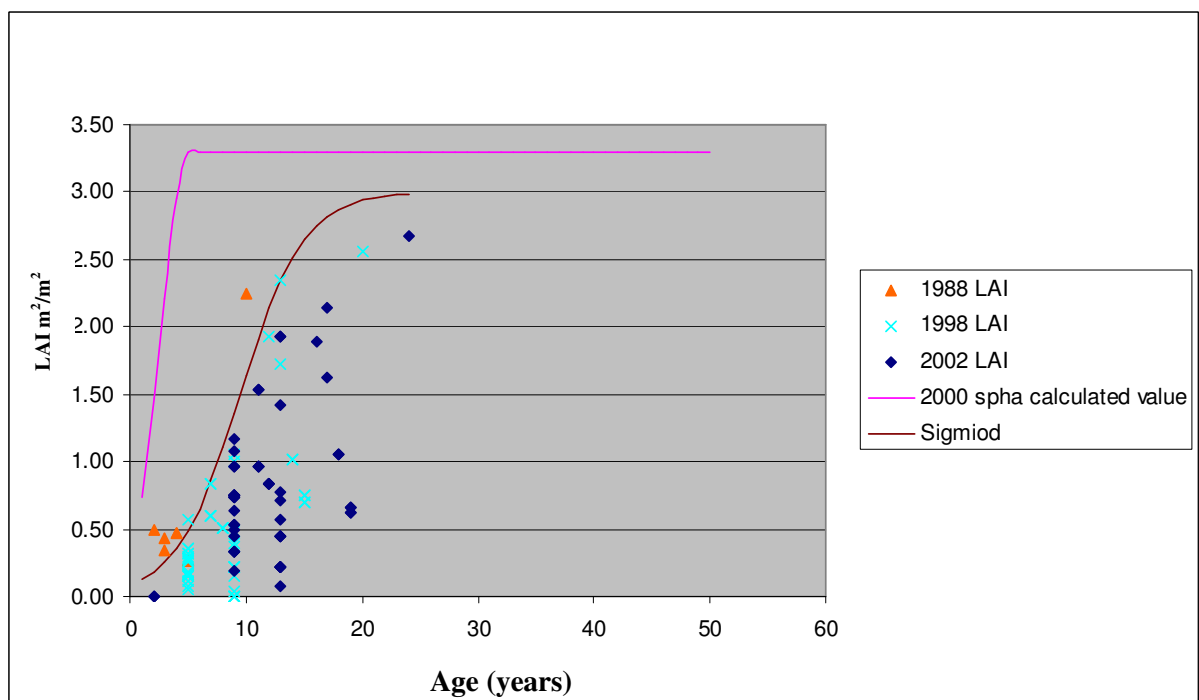


Figure 46. 2000 stems/ha LAI comparison of satellite data, regression analysis and sigmoidal growth pattern

With the exception of the 1300 stems/ha (Figure 44) the sigmoidal early growth pattern found is a better fit for maximum achievable LAI for stands below 20 years of age that have not been thinned. Currently FPC is not thing stands until after 20 years old and if a thinning was done in the past then stands where reduce to approximately 700 stems/ha

#### **x) LAI annual growth and rainfall at Gngangara Mound for *P. pinaster* Aiton**

Plot data from the basal area thinning trials in *P. pinaster* Aiton which were established in 1965 and 1966 on Gngangara Mound (Hopkins and Butcher 1999), were investigated to determine if a relationship could be found for annual LAI regrowth following thinning across a range of basal areas.

The Gngangara trial consisted of basal area treatments of 37, 25, 16, 11 and 7 m<sup>2</sup> ha<sup>-1</sup> with five replications and was established in 19 year old stands in 1965. At Yanchep, the trial was established in 1966 in 14 year old stands with a similar design to that at Gngangara plantation except that the 37 m<sup>2</sup> density treatment was omitted. The basal area classes were maintained by regular thinning until 1980. Annual measurements were carried out to 1985 for Gngangara and 1986 for Yanchep.

The measurements of basal area and stocking data were converted to LAI using the relationship, developed by CSIRO (Hodgson 2003), between Leaf Area per tree and basal area per tree when forced through the origin. This is approximately  $LA\ (m^2) = 865 * Basal\ area\ (m^2)$  (Robert Stokes 2003, Principal Engineer Integrated Water Supply, Water Corporation pers. comm.). This is equivalent to diameter squared by 0.07. A forced maximum of 3.3 was imposed upon this formula as previously discussed as the site maximum for *P. pinaster* Aiton. This effectively meant that the 37 m<sup>2</sup> ha<sup>-1</sup> basal area treatment at Gngangara plantation was near or at the site maximum for most of the time. Consequently it was not able to be used for the annual LAI increment calculations. The resulting conversion to LAI is shown in Figure 48 for Gngangara and Figure 47 for Yanchep.

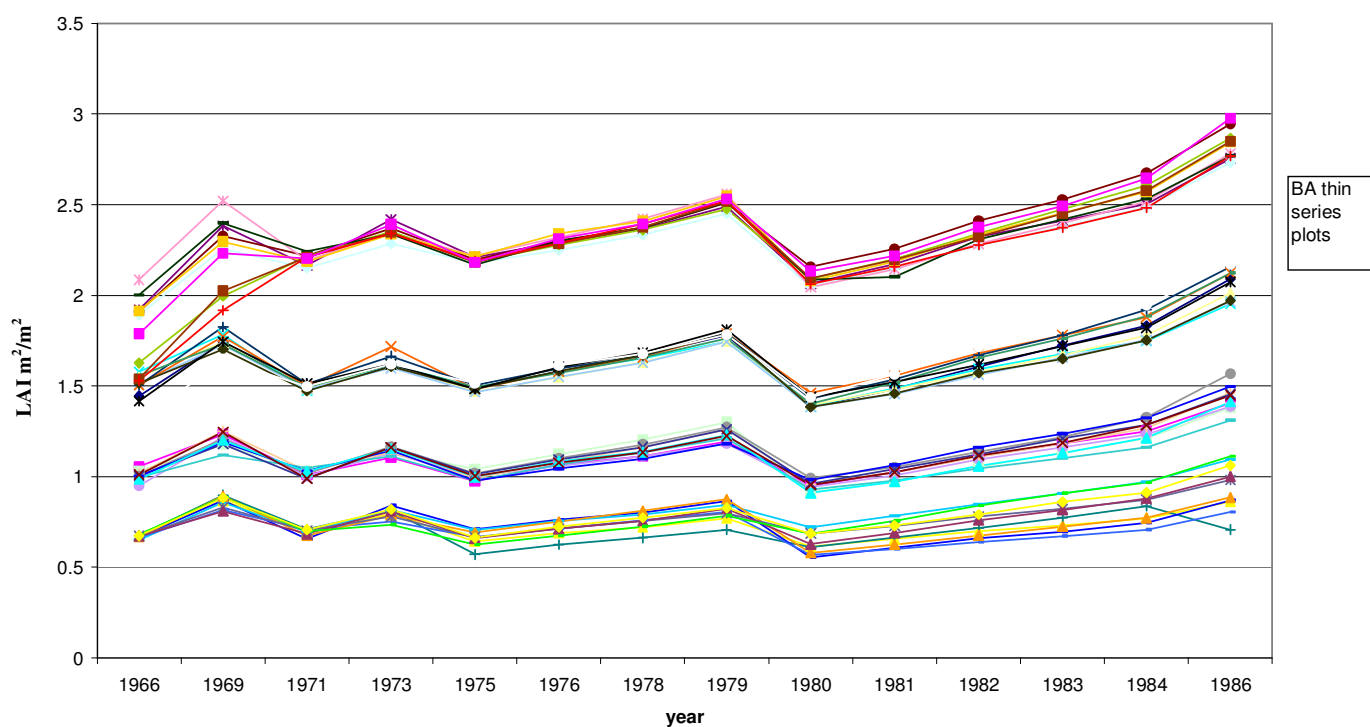


Figure 47. Derived LAI for BA thin series Hopkins 54/66 series Yanchep basal area treatments of 25, 16, 11 and 7  $\text{m}^2 \text{ha}^{-1}$

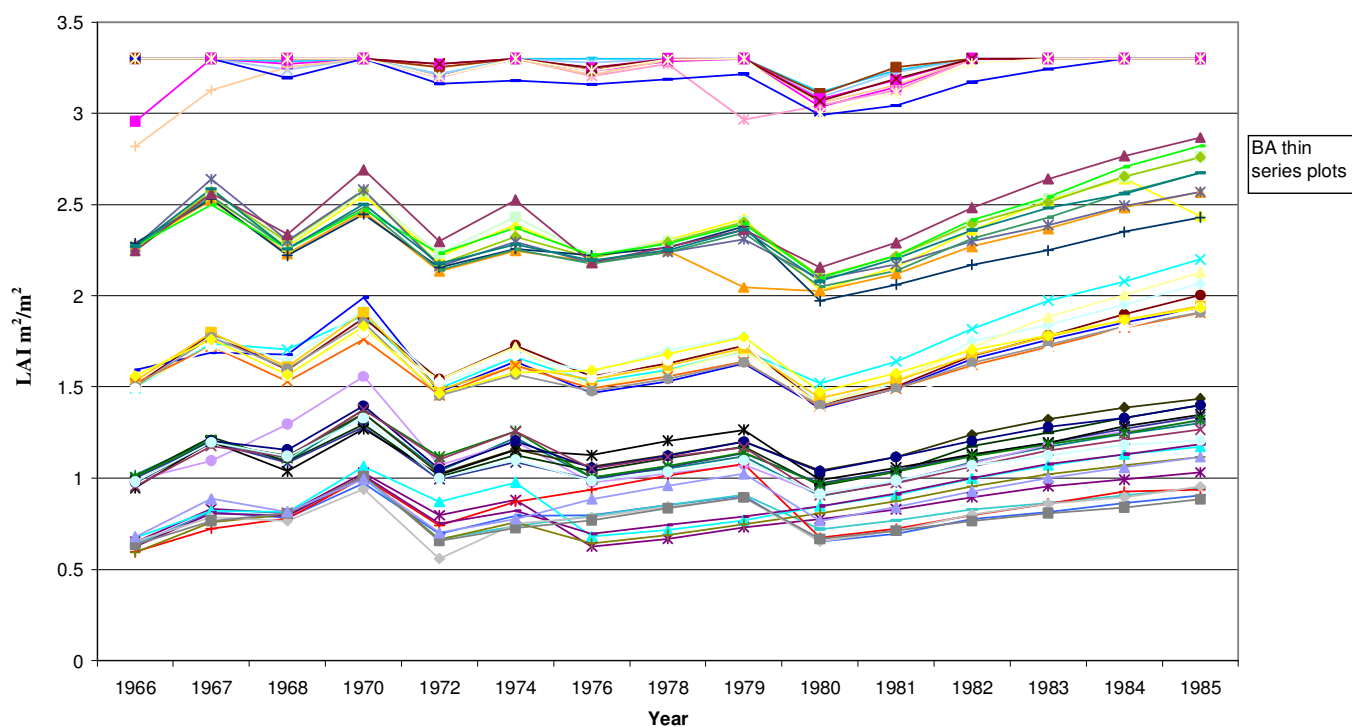


Figure 48. Derived LAI for BA thin series Hopkins 20/65 series Gngangara basal area treatments of 37, 25, 16, 11 and 7  $\text{m}^2 \text{ha}^{-1}$



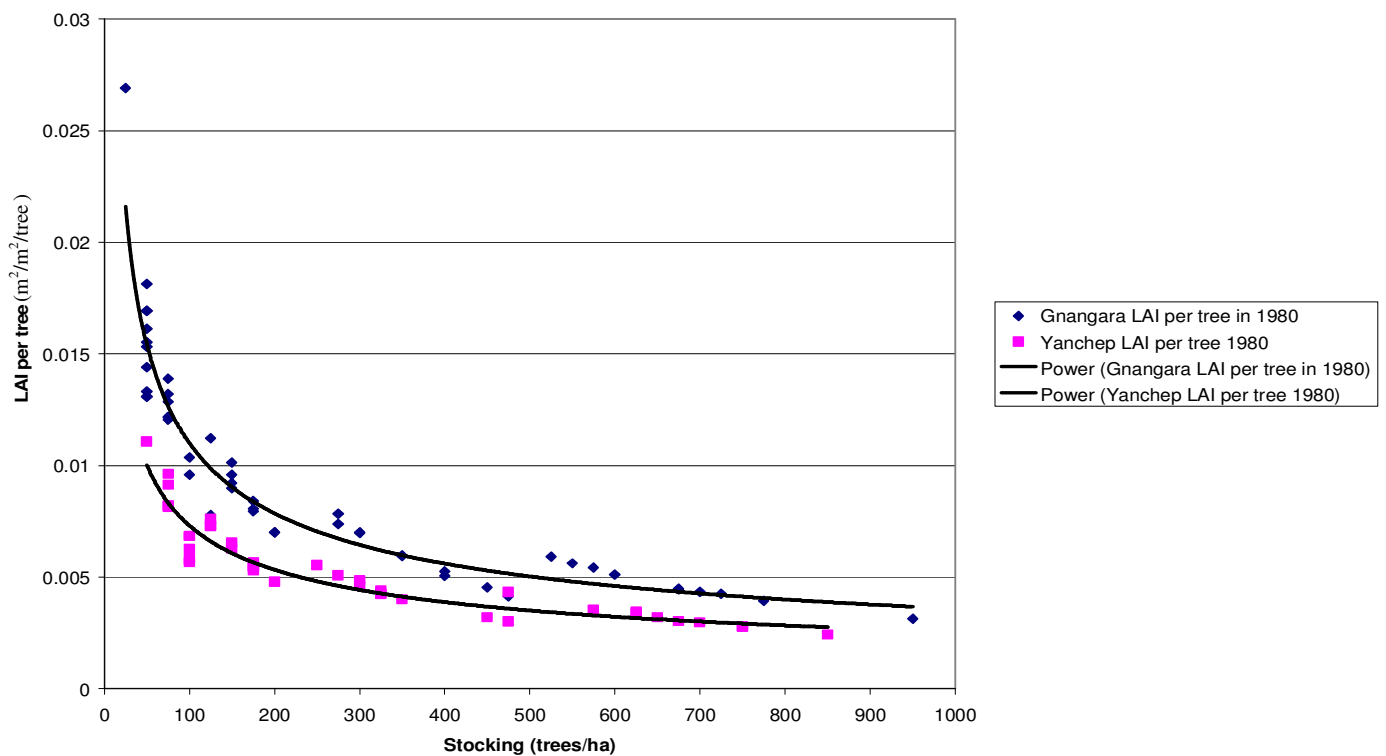


Figure 49. LAI per tree vs stocking for Gngangara and Yanchep series in 1980

Average LAI per tree was derived from stand LAI divided by stand stocking (stems/ha)

In Figure 49 the Gngangara series were 6 years older than the Yanchep series. The Yanchep series LAI per tree for a particular stocking is consistently less than the Gngangara series.

Figure 49 shows a consistent pattern across a range of stockings of increasing LAI per tree with increasing age.

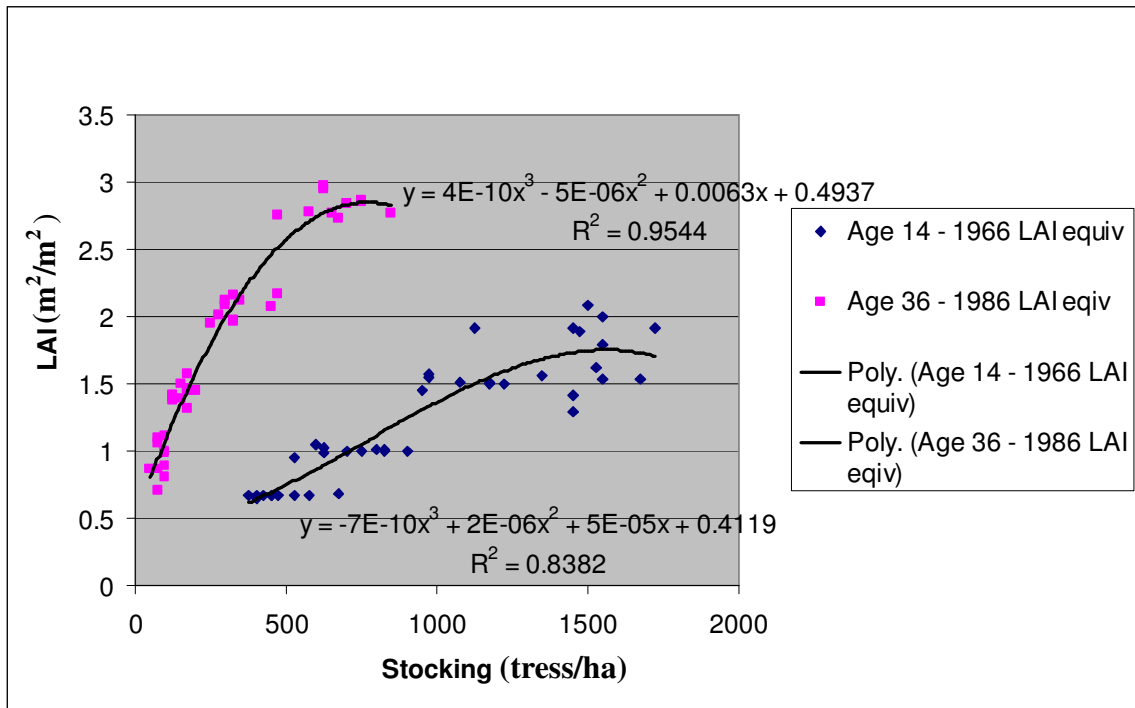


Figure 50. Derived LAI for Yanchep series at the age 14(beginning of trial) and age 36 (end of trial)

Analysis of derived LAI figures does give a consistent result with known LAI behaviour with a high level of consistency across the range of replications (Figure 50). The above analyses demonstrated that it would be possible for this data set from Hopkins and Butcher 1999 to use derived LAI ( that is equal to diameter squared by 0.07) values in subsequent modelling.

There were two periods of sustained growth during the trials between thinning events in both the Gngangara and Yanchep series. These two periods were 1976 to 1979 and 1980 to 1985 at Gngangara plantation. At Yanchep plantation, they were 1975 to 1979 and 1980 to 1986. These two periods at each site have significantly different annual average rainfalls as recorded at Wanneroo. For Gngangara the average for 1976-1979 was 653 mm and for 1980-1985 738mm, a difference of 85mm. For Yanchep the average for 1975-1979 was 633mm and for 1980-1986 756mm, a difference of 123mm. Both annual average LAI growth per tree and for stands (Figures 51, 52, 53 and 54) show a consistent pattern of reduced LAI annual growth for reduced average annual rainfall.

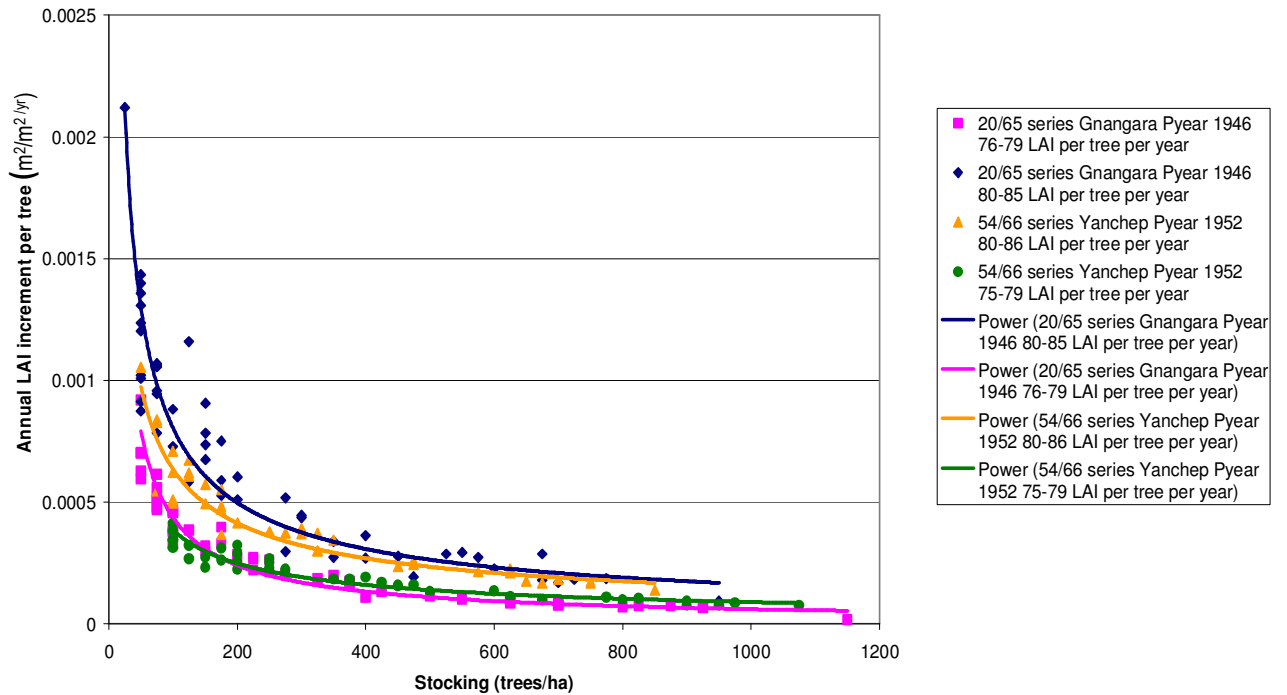


Figure 51. Average annual LAI growth per tree across a range of stockings for different rainfall periods in Gngangara and Yanchep series

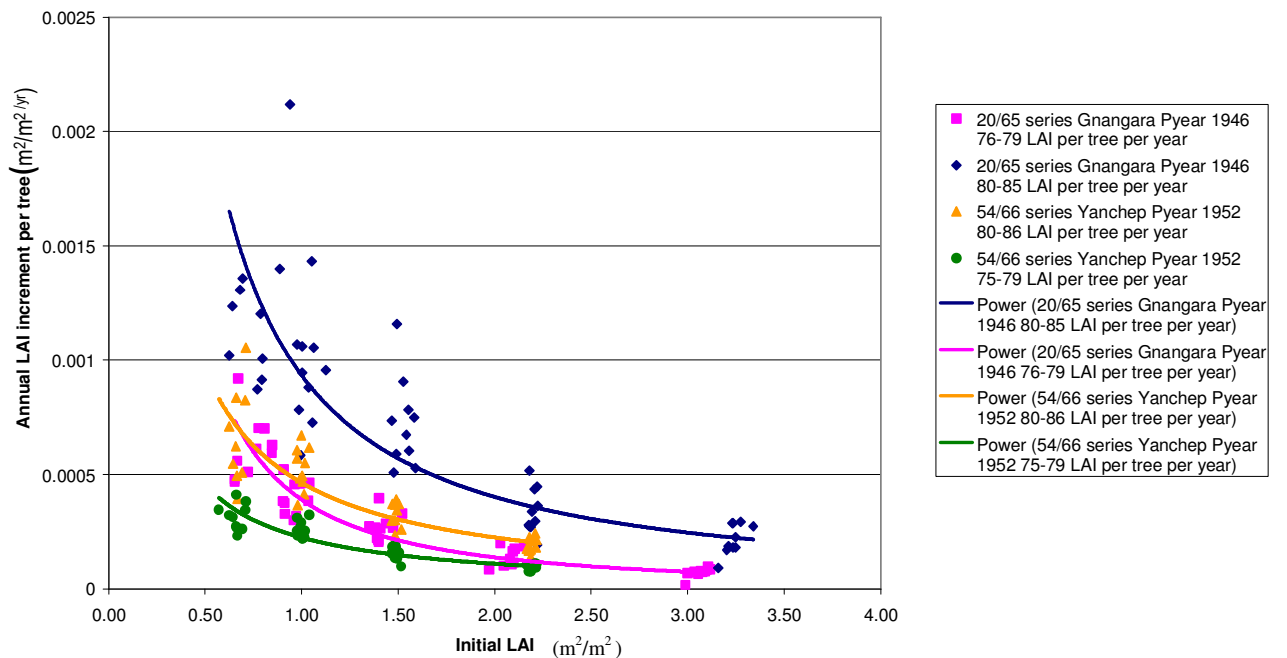


Figure 52. Average annual LAI growth per tree across a range of initial LAI values for different rainfall periods in Gngangara and Yanchep series

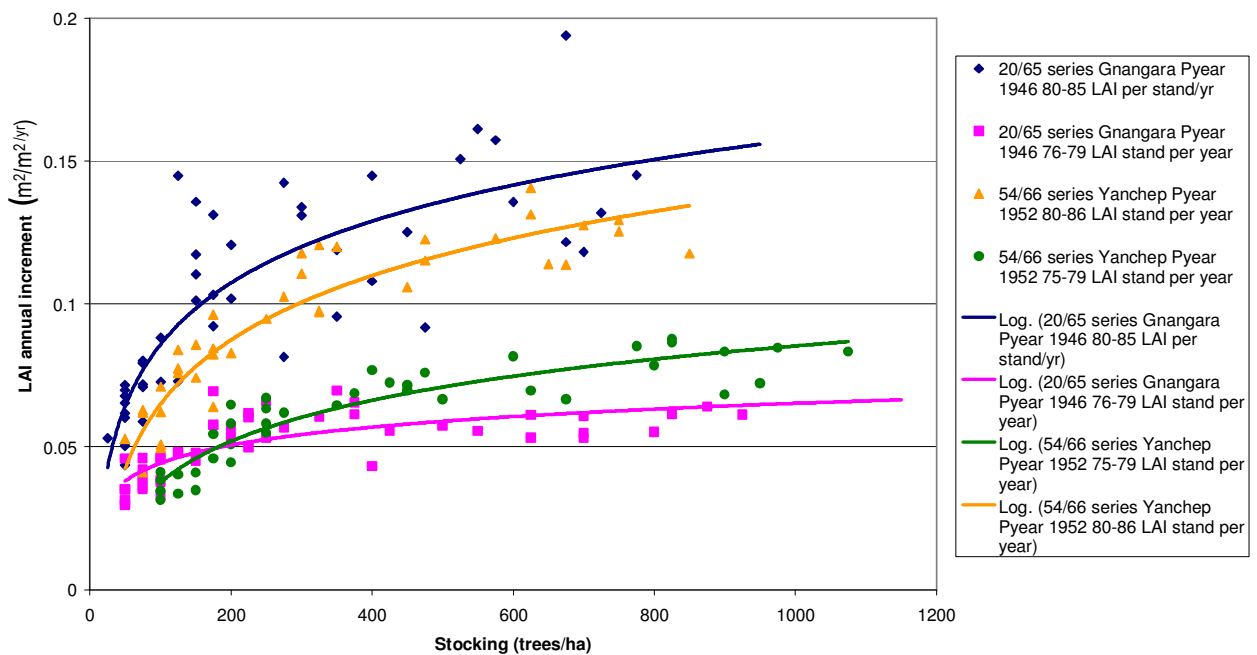


Figure 53. Average annual LAI growth for stands across a range of stocking values for different rainfall periods in Gngangara and Yanchep series

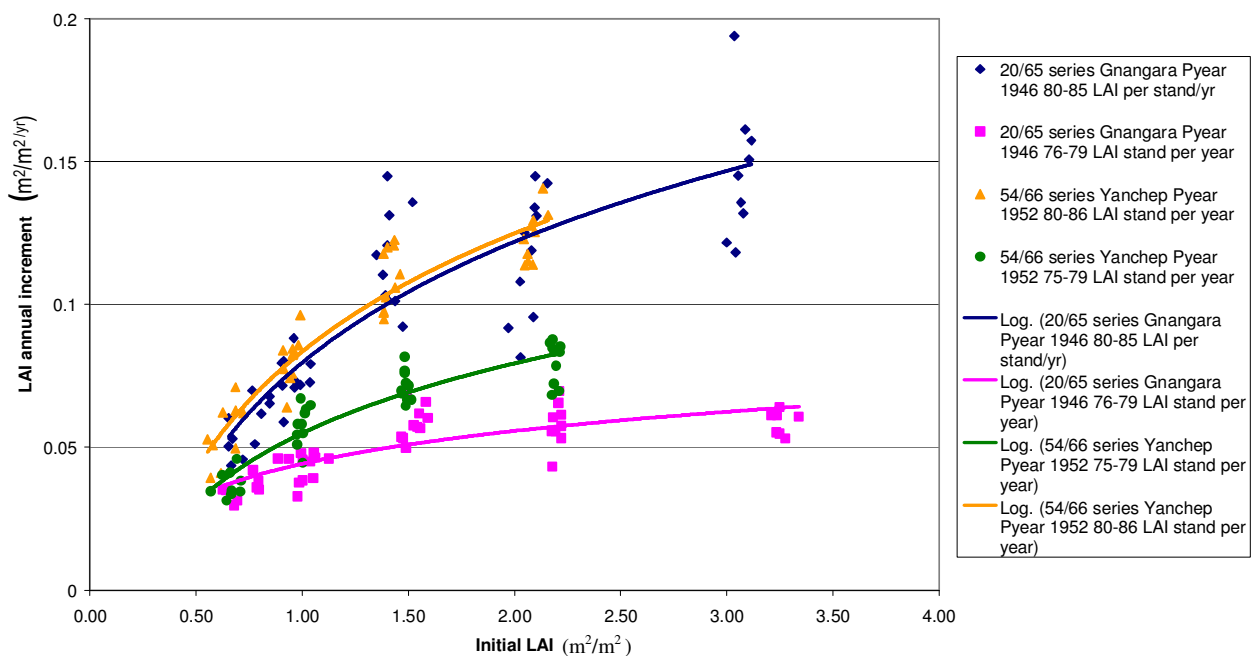


Figure 54. Average annual LAI growth for stands across a range of initial LAI values for different rainfall periods in Gngangara and Yanchep series

#### xi) LAI after thinning for *P. pinaster* Aiton at Gnangara Mound

There are difficulties in determining the relationship between stocking and LAI reductions following thinning because LAI values are only available every second year. To reduce this problem it was decided to take a sample of areas thinned in the same year that LAI values were available. This should minimise the impact of mis-matching LAI values to thinning times. It was considered that this would then provide some indication of the likely relationship between reduction in stocking following thinning and the reduction in LAI observed. Stands from Pinjar representing several planting years and both first and second thinning harvesting operations from 2001 were chosen for the sample.

This showed that there is a weak direct relationship between stocking reduction and LAI reduction (Figure 55). The poor correlation is most likely caused by the LAI values not being available directly before and directly after the thinning and variations between the stocking levels recorded for the stands and those actual achieved. The arithmetic average difference for percentage reduction of stocking versus percentage reduction of LAI for the samples was only -2%.

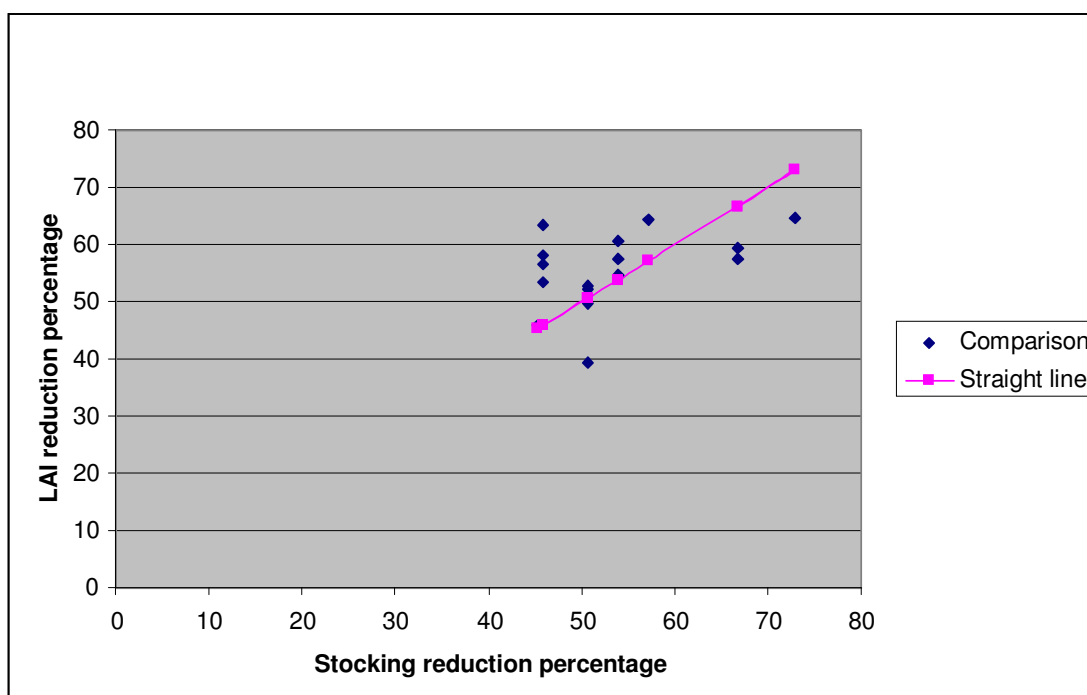


Figure 55. Comparison of Stocking and LAI reductions following thinning in Pinjar sample

Plot data from the basal area thinning trials in *P. pinaster* Aiton (Hopkins and Butcher 1999) were again investigated to see if a more consistent relationship between percentage LAI removed and percentage stocking reduction could be demonstrated. The Yanchep plots thinning which was carried out in 1979 were the most representative of the range of thinnings being modelled later in that the percentage stocking removed is very similar at a similar age to that modelled. It was several years after the previous thinning and this allowed for growth and hence LAI to recover sufficiently after thinning (Figure 56).

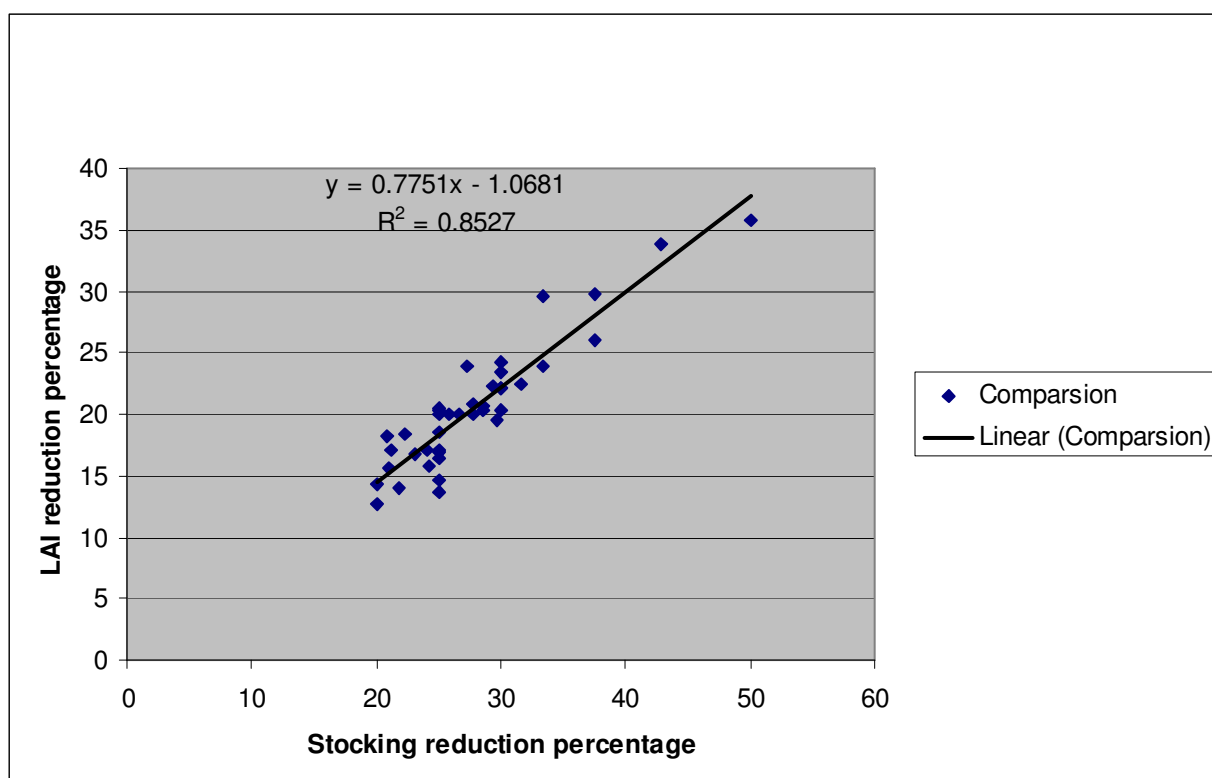


Figure 56. Comparison of Stocking and LAI reductions in Yanchep BA and thinning trial in 1979

The relationship of stocking reduction percentage to LAI reduction percentage from Figure 56 is linear with LAI reduction being 80% of the stocking reduction percentage. For example, a 50% reduction in stocking at a thinning equates to a 40% reduction in LAI.



**xii) LAI, low stocking and understorey for *P. pinaster* Aiton at Gnangara Mound**

Field observations of low stocked areas revealed that there can be large open areas between trees and these gaps may have under-storey that could reflect back values of up to a LAI of approximately  $0.5 \text{ m}^2/\text{m}^2$  (Figures 57 and 58). Consequently, some caution is required when LAI is derived from satellite photography for very low stocked stands. Show on map



Figure 57. P64 Pinjar understorey (Pine reported LAI 2002 of 2.12) Pine 65 stems/ha

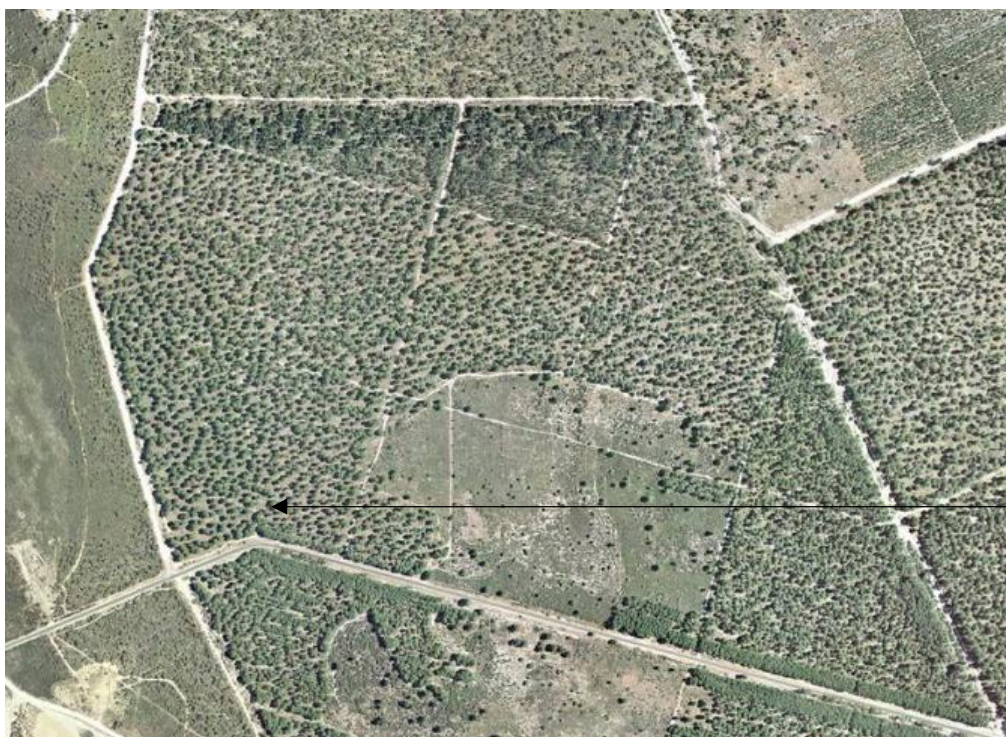


Figure 58. Airphoto from 2003 of Pinjar P64

Figure 59 location

### xiii) Discussion of results

The results for *P. pinaster* Aiton can be summarised as follows:-

- Basal area, age and stocking alone were not able to describe the LAI pattern.
- Maximum LAI on Gwangara Mound is approx  $3.3 \text{ m}^2/\text{m}^2$ .
- High basal area did not always correspond with high LAI.
- Annual LAI growth could be described post thinning by combining both stocking and age with a correlation coefficient of 83%. This result was robust enough to use in subsequent modelling.
- The formula for LAI annual growth that has been derived does not plateau at a site maximum. Consequently, it should only be applied to produce values that are less than LAI  $3.3 \text{ m}^2/\text{m}^2$ . In the absence of any thinning this will make the formula for LAI equal to the LAI of the previous year plus the appropriate annual LAI growth, provided that this sum is less than  $3.3 \text{ m}^2/\text{m}^2$ . If prediction is greater than  $3.3 \text{ m}^2/\text{m}^2$  then LAI becomes  $3.3 \text{ m}^2/\text{m}^2$ .
- The area of very old stands (those greater than 75 years old) is very small and making the LAI growth negative would have introduced illogical results in the optimization used in the linear programming model. Consequently negative growth values for LAI in the model domain were modified to leave LAI equal to the previous years LAI if LAI growth predicted is negative.
- Young stands below 20 years old did not grow according to the annual LAI growth formula predicted for older stands after thinning. A sigmoidal growth curve was found to fit the young stand LAI growth data with a correlation coefficient of 84.4%. This pattern can be explained if there is a period once the stands are established of exponential growth in LAI. But, as the population grows, individual trees begin to interfere with each other in competition for a critical resource. This competition diminishes the LAI growth rate, until it ceases to grow and maximum LAI is reached.



One resource constraint is a lack of a continually growing amount of available water for individual trees. As trees within a stand continue to grow, they reach a point (canopy closure) where there is no longer a surplus of water around them as their neighbours have already accessed it. For young *P. pinaster* Aiton LAI continues to grow until little or no water recharge occurs below it at maximum LAI (This will be discussed in chapter 6). It is reasonable to assume that stand water use for *P. pinaster* Aiton on the Gngangara Mound generally follows this sigmoidal pattern when plotted against age.

- Average annual LAI growth per tree showed a reduction with reducing average annual rainfall. LAI annual growth is then dependent on annual rainfall
- Reduction of percentage LAI after thinning was linearly related to 80% of stocking reduction. This is a logical result as normally thinning removes the smaller trees, which would have both less volume and less leaf area than the average for the stand.
- Caution will be required in the use of LAI values of low stocked areas as these are likely to over represent the true LAI value of the contribution of *P. pinaster* Aiton.

Using the findings above LAI growth for a stand over time for *P. pinaster* Aiton at Gngangara Mound can be predicted. At any one point in time LAI would be somewhere along a sigmoidal path between zero and the site maximum for the species, so long as the stand occupies sufficient of the area to be able to command the majority of the available soil water. If the stand remains unthinned, then age (at least up until age 20 years old) can be used to determine where the stand is upon the sigmoidal path of growth. Thinning resets the stand back to a point approximately equal to the percentage of crown area removed. For example if forty percent of the crown is removed from a stand such as in a typical thinning involving a 50% reduction in stocking and the stand has attained a leaf area of LAI 3 m<sup>2</sup>/m<sup>2</sup> just prior to the thinning, then after the thinning it would be reduced to 1.8

LAI  $\text{m}^2/\text{m}^2$ . The stand then would proceed to grow back leaf area overtime to try and fully reoccupy the area and hence regain the site maximum for the species. Consequently, for thinned stands the intensity and timing of thinning and time since thinning are important factors in determining the LAI at any one point. An example of a stands LAI profile over time is shown in Figure 59. It has an arithmetic average LAI  $1.7 \text{ m}^2/\text{m}^2$  for the life of the stand.

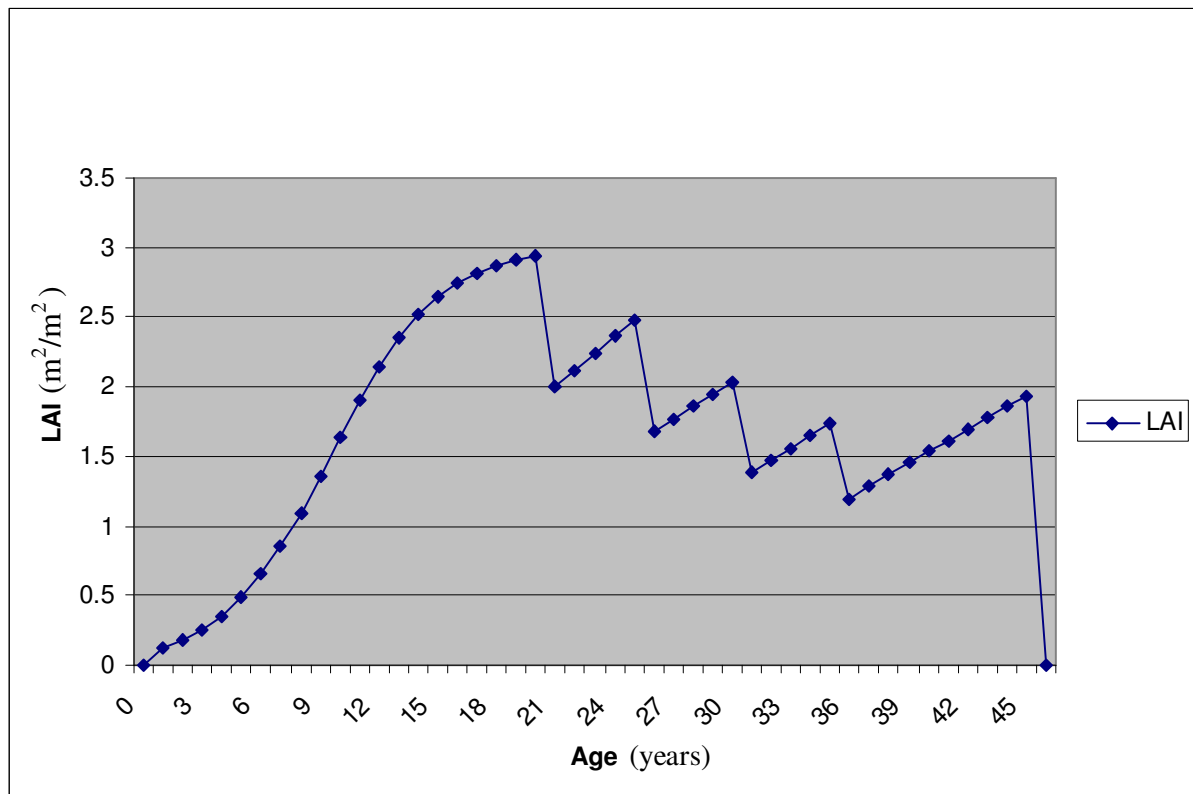


Figure 59. An example stand LAI track with age for 4 thinnings and clearfall at age 45

## **6. Groundwater recharge relationships to Leaf Area Index in *Pinus pinaster* Aiton on Gnangara Mound**

The following issues will be addressed in this chapter:-

- What factors need to be considered in quantifying the water use of *P. pinaster* Aiton plantations?
- At what point does the LAI stop effective recharge?
- What is the most likely configuration of the LAI to recharge relationship and how does this vary with age and depth to groundwater?

### **i) *Banksia* sp. woodland and *P. pinaster* Aiton water use on the Gnangara Mound**

Farrington et. al. (1989) measured evapotranspiration from *Banksia* sp. woodland on the Gnangara Mound. Farrington et. al. (1989) found that for this vegetation community depth to groundwater had little or no effect on evapotranspiration and that the *Banksia* sp. and *Adenanthos* sp. contributed only 36% (240mm) of the annual evapotranspiration. The site contained thick ground flora, which grows roots to a similar depth as the trees and shrubs. The shrub and herbaceous ground flora layer contributed 64% (426mm) of the site's evapotranspiration. Where the water table was within 5.4 metres of the ground surface, roots extended to that level. Upslope, where the depth to groundwater was deeper roots were sparse below 8 metres depth. Evaporation for the whole vegetation community totalled 666 mm per year or 77% of the 863 mm annual rainfall. Hence, in their study area recharge was 23 % during the study. As this site is close to that reported in Farrington et. al. (1990), it is believed that it was burnt at the same time (6 years before the study).

Farrington et. al. (1989) points out that there are important management implications from their study. For example, ground flora evaporation is a major component of the water use of

*Banksia sp.* woodland. If ground flora were reduced by 50%, it would be expected to increase the recharge to 48% of annual rainfall. If prescribed burning is used to achieve this it could be expected that the regeneration of the biomass would reach a new lower plateau. A regular burning program at specified intervals would be necessary to keep the evaporation rates of the ground flora at a low level.

A further implication of the finding that the ground flora is a significant water user is that any scrub layer that recovers below pines once the canopy is opened sufficiently would significantly increase water use despite the reduction of the canopy overstory. It would be important to ensure the gains to recharge by pine thinning are not lost through understorey water use below the pine canopy.

Farrington et. al. (1990) measured evapotranspiration from vegetation growing in a small, seasonally waterlogged basin on the Gngangara Mound. It is unclear from their report how much of the Gngangara Mound these “damplands” sites occupy. They are part of the wetlands of the Bassendean dune system that are at the bottom of the interdunal swales where the water table intersects the ground surface. The site of the study was burnt 7 years prior to the study period. The dominant tree species at the site is *Melaleuca preissiana* Schauer with other *Melaleuca sp.* and *Banksia sp.* species being subdominant. Shrubs formed a dominant component of the community around the edge of the depression (including species of *Regelia sp.*, *Hypocalymma sp.* and *Pultenaea sp.*) and in the waterlogged area (*Leptospermum sp.* and *Astartea sp.*). The reed *Baumea articulata* R.Br. is dominant in small areas where free water persists at the surface in summer. Total annual evaporation was 814 mm or 109% of annual rainfall. There was a fresh water table within 3 metres of the ground surface at all times, even at the upslope edge of the site, and some areas of free water persisted during summer.

Farrington et. al. (1990) report that there was water at the surface even in summer and the

evaporation of greater than 100% of rainfall measured at the site. This would indicate that the groundwater mound was exposed at this site and was directly evaporating away.

Raper (1998) suggests that measurements made with the ventilated chamber technique, which indicates that tree water use may exceed annual pan evaporation under highly favourable conditions, may be in error. Raper (1998) states, “at the very least they should be viewed as the extreme upper limit to tree water use under ideal conditions and extrapolating these figures to other areas or periods would be optimistic in the extreme” (p. 32).

Carbon et. al. (1982) carried out soil water measurements with a neutron moisture meter every six weeks for periods ranging from 378 to 489 days for areas of both native vegetation and *P.pinaster* aiton on Gngangara mound. Carbon et. al. (1982) found that at 1200 stems.ha<sup>-1</sup> 14 year old *P. pinaster* Aiton plantations on the Swan Coastal Plain extracted soil water from beyond 6 metres depth and their total evapotranspiration (including interception) was between 96% and 105% of the rainfall for the measurement period. Carbon et. al. (1982) also determined the water use of native vegetation communities on the Swan Coastal Plain in 1965 to 1967. Carbon et. al. (1982) monitored the rainfall and soil moisture at three sites with average annual rainfall of 800 to 900 mm per year. A deep, permanent water table was present at 15 to 20 metres depths at each site. A forest dominated by *Eucalyptus marginata* Donn ex Sm., *E. gomphocephala* DC., and *Banksia grandis* Willd covered the first site.

Evapotranspiration over the period of the study was 105% of the rainfall. The vegetation at the second site was dominated by *E. marginata* Donn ex Sm, *E. todtiana* F.Muell., and *B. grandis* Willd. Evapotranspiration over the period of the study was 70% of rainfall. The third site, dominated by *B. attenuata* R.Br. and *B. menziessi* R.Br., had evapotranspiration of 49% of rainfall. Unpublished studies on thinning trials in Myalup and McLarty plantations west of Harvey in the south west of WA, (Ian Dumbrell 2008, Research scientist Forest Products

Commission pers. comm.) also point to negligible recharge under *P. pinaster* Aiton stands greater than 500 stems/ha at age 17, 18 m<sup>2</sup> basal area. Myalup and McLarty plantations have slightly higher annual rainfall at 840mm per annum and similar evaporation to Gnangara mound . They are also on the swan coastal plain of South Western Australia and have similar depth sandy soils as Yanchep and Pinjar plantations.

Butcher (1997) reports on a study that was carried out on stands planted in 1952 with an initial stocking of 2200 stems/ha. A thinning experiment was established in 1966 to test the effect of stand density on groundwater recharge. The stands were periodically thinned to maintain the target basal area over time for four treatments of 35, 25, 11 and 7 m<sup>2</sup> basal area. Soil water content was estimated using a neutron attenuation technique from 1968 to 1975 to a depth of 6 metres. Rainfall through fall beneath the stands was directly measured and rainfall interception was then derived from these values when this was compared to open cover rainfall gauges. The stand data for this study is unpublished (Trevor Butcher 2007 Research scientist Forest Products Commission pers. comm.).

Butcher (1977) found that :-

- Rainfall interception by *P. pinaster* Aiton increased from 10% in 7 m<sup>2</sup> basal area sites to 26% in 25 m<sup>2</sup> basal area sites. Butcher (1977) suggests the relationship between basal area and rainfall interception has a major bearing on the recharge below the stand. Butcher (1977) also suggests that further losses to recharge are caused by an increasing needle bed and humus layer with increasing stand density.
- No soil wetting front for the 25 m<sup>2</sup> site was recorded below 6 metres soil depth. Considerable recharge however occurred under native woodland and open pine (*P. pinaster* Aiton) stands below 7 metres soil depth. The soil moisture withdrawal for the 11 m<sup>2</sup> basal area pine (*P. pinaster* Aiton ) stand was similar to the native woodland site. One major difference however, is that below 5 metres soil depth the native

woodland appears to remove more soil moisture than the 11 m<sup>2</sup> basal area pine (*P. pinaster* Aiton) stand. This may however, reflect the greater amount of soil moisture under the native woodland relative to the pine (*P. pinaster* Aiton) stand.

Sharma, Barron and Craig (1991) undertook a study on Gngangara mound , using the chlorine method, from 1983 to 1987. Sharma, Barron and Craig (1991) examined the differences in depth to water table and recharge in dense (basal area 48 m<sup>2</sup> /ha) and thinned (9.5 m<sup>2</sup> basal area) pine (*P. pinaster* Aiton) stands versus *Banksia sp.* stands. 1985 was a poor rainfall year (621mm at Wanneroo) at these pine sites and this may have significantly influenced the results.

Sharma, Barron and Craig (1991) found on a deep (20m) to water table site : -

- Negligible rainfall recharge occurred beneath dense (originally planted at 2200stems/ha) mature pines (*P. pinaster* Aiton) planted in 1957. The stand of pines was 16 metres high with basal area of 48 m<sup>2</sup> /ha when the study was carried out. Stands of this density are now rare on the Gngangara Mound.
- 15% rainfall recharge in *Banksia sp.* considered typical and in pristine condition. From this it could be hypothesised to be a site long unburnt. The density and structure of the *Banksia sp.* at this site is unreported in the study.
- 32% rainfall recharge beneath young pines (*P. pinaster* Aiton), planted in 1976 originally planted at 1150 stems/ha and thinned to 300 stems/ha in 1980. The stand was six metres high with a basal area of 5 m<sup>2</sup> when the study was carried out.
- Using the bromide method they calculated that recharge for their deep to water table *Banksia sp.* site averaged 7% over the five year period of the study.

On the shallow water table sites, they found: -

- That for dense pine (*P. pinaster* Aiton) planted in 1946 with a basal area of 30 m<sup>2</sup> in 1985 and height of 15 metres, water table at 4.5 metres depth, interception was 30% of rainfall and using the bromide and chloride methods and recharge was 8% and <12% respectively.
- For the low density pine site (*P. pinaster* Aiton) planted in 1946 site, 9.5 m<sup>2</sup> basal area in 1985 and thinned that year to this level, 15 metres high water table at 6 metres depth, interception was 20% of rainfall and using the bromide and chloride methods recharge was 16% and <16% respectively.
- For the *Banksia* sp., which was sited on an area seven metres to water table (measured over a different time frame and at different water table depths making comparisons difficult), interception was 15% of rainfall and for the chloride method 31% recharge and the bromide method 32% recharge.

Sharma, Barron and Craig (1991) attributed the difference in *Banksia* sp. recharge between the two sites to the difference in understorey vegetation because at the deep to ground water site it was much denser. This would agree with the Farrington et. al. (1989) model of the relationship between density of ground flora and recharge. Their modelling showed that a reduction of LAI from six to one would reduce the interception from 29% to 10% and because of this reduction and lower transpiration at one LAI recharge is doubled in their model.

Farrington and Bartle (1991) estimated recharge for both *Banksia* sp. and *P. pinaster* Aiton from 1985 to 1988. The average recharge over the three years was 15% for the pine (*P. pinaster* Aiton) and 22% for the *Banksia* sp. woodland. The *Banksia* sp. site had 410 trees per ha with a basal area of 5 m<sup>2</sup>. The pine (*P. pinaster* Aiton) site was established in 1967 and thinned to 750 stems/ha approx. in 1972. At the time of the study stocking was 630 stems/ha and basal area 30 m<sup>2</sup>. A permanent water table at both sites was between five to eight metres below the surface. Farrington and Bartle (1991) found the throughfall was similar for pine (*P.*



*pinaster* Aiton) and the *Banksia sp.* Farrington and Bartle (1991) suggest that the difference was due to a combination of additional evapotranspiration by pine (*P. pinaster* Aiton) over *Banksia sp.* woodland and the presence of needle bed under the pines. This study suggests that regular underpine burning to reduce needle bed depths may be as important as thinning to increase recharge.

Butcher (1979) found that for the first 10 years after pine (*P. pinaster* Aiton) planting recharge was greater than in native *Banksia sp.* stands. It took 10 years after pine (*P. pinaster* Aiton) planting for the recharge below those stands to return to equivalent native levels. This would seem to agree with the formula used by Water Corporation that recharge below 0.5 LAI is 45 % and that from 0.5 to 1.5 m<sup>2</sup>/m<sup>2</sup> LAI decreases linearly (Robert Stokes 2003, Principal Engineer Integrated Water Supply, Water Corporation pers. comm.).

The important points from above can be summarised as :-

- *P. pinaster* Aiton stands that are young (under 10 years old and) or are of low basal area (below 11 m<sup>2</sup>) and hence low LAI allow ground water recharge at or greater than native vegetation on Gngangara Mound.
- At canopy closure of *P. pinaster* Aiton stands, ground water recharge appears to be extinguished.
- Fire impacts groundwater recharge because it reduces ground cover lowering the vegetations water usage and hence increasing recharge.

Much of the Gngangara Mound *P. pinaster* Aiton is now less than 250 stems/ha (Figure 60). This factor will need to be taken into account when prescribing future outcomes for recharge as many of the previous studies looked at areas with significantly larger stockings.

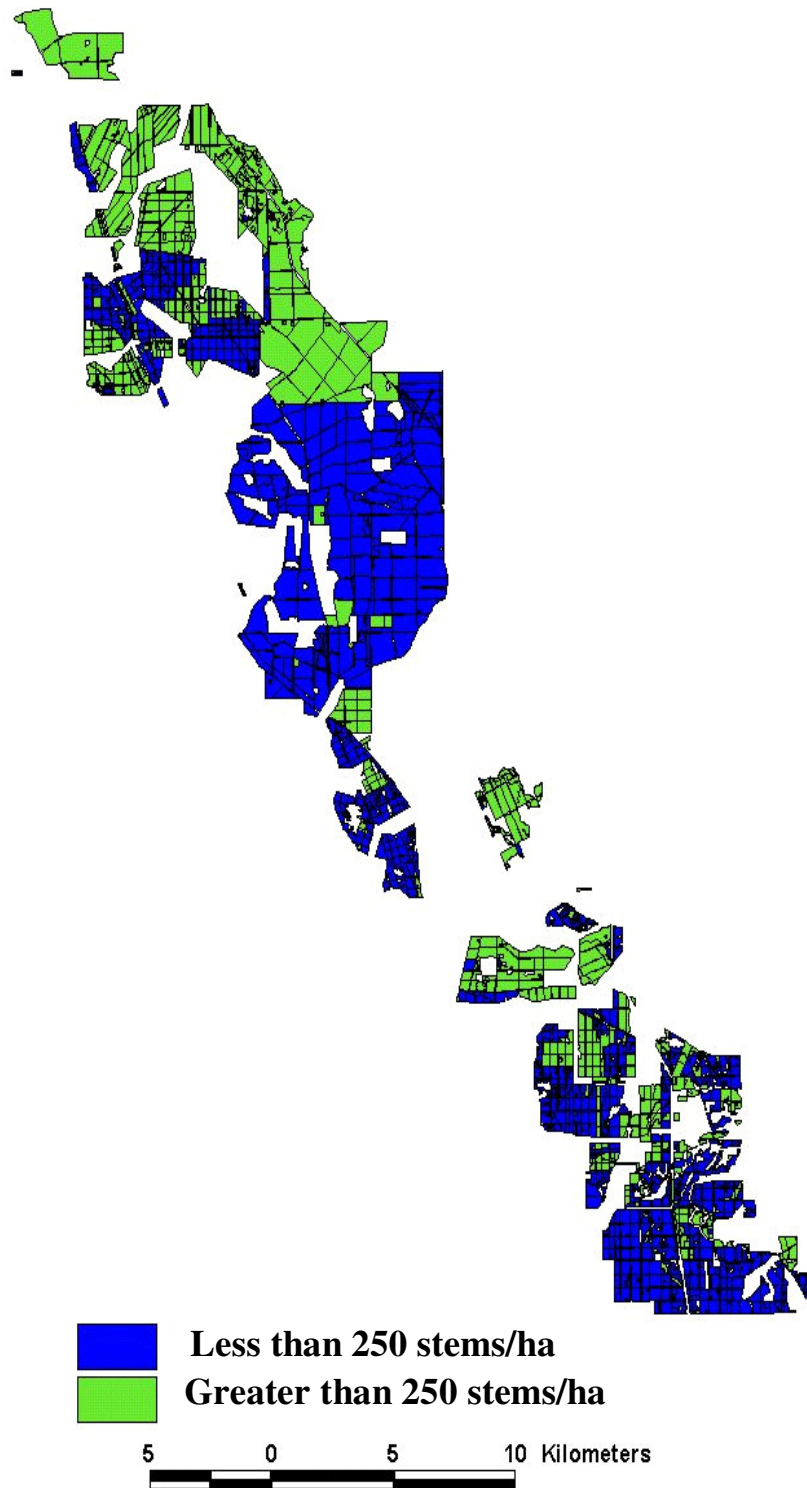


Figure 60. 2002 stocking levels of the Gwangara plantations

## **ii) *P. pinaster* Aiton LAI and depth to water table at Gnangara Mound**

Evidence of suppression of maximum LAI can be seen from both the 1978 and 1967 plantings. The 1978 plantings on shallow water tables in Pinjar plantation had a lower LAI of  $2.6 \text{ m}^2/\text{m}^2$  prior to the thinning in 2001 than the areas with deeper water tables which had an LAI of  $2.96 \text{ m}^2/\text{m}^2$ . The 1967 plantings on shallow depths to water table have not exceeded LAI's of  $2.4 \text{ m}^2/\text{m}^2$  in Gnangara plantation whereas it would have been expected it to reach  $3 \text{ m}^2/\text{m}^2$ . It also had lower height growth on shallow depths to water as previously noted in chapter 2.

Depth to water table at the end of summer 2002 below Gnangara Mound plantations shown in Figure 12 was combined with the LAI data derived from the satellite sequence to produce a data set that shown maximum LAI for different depth to water table classes and was further subdivided into planting decades. The results are shown in Figure 61.

Maximum LAI by Depth to Water table and Pyear class

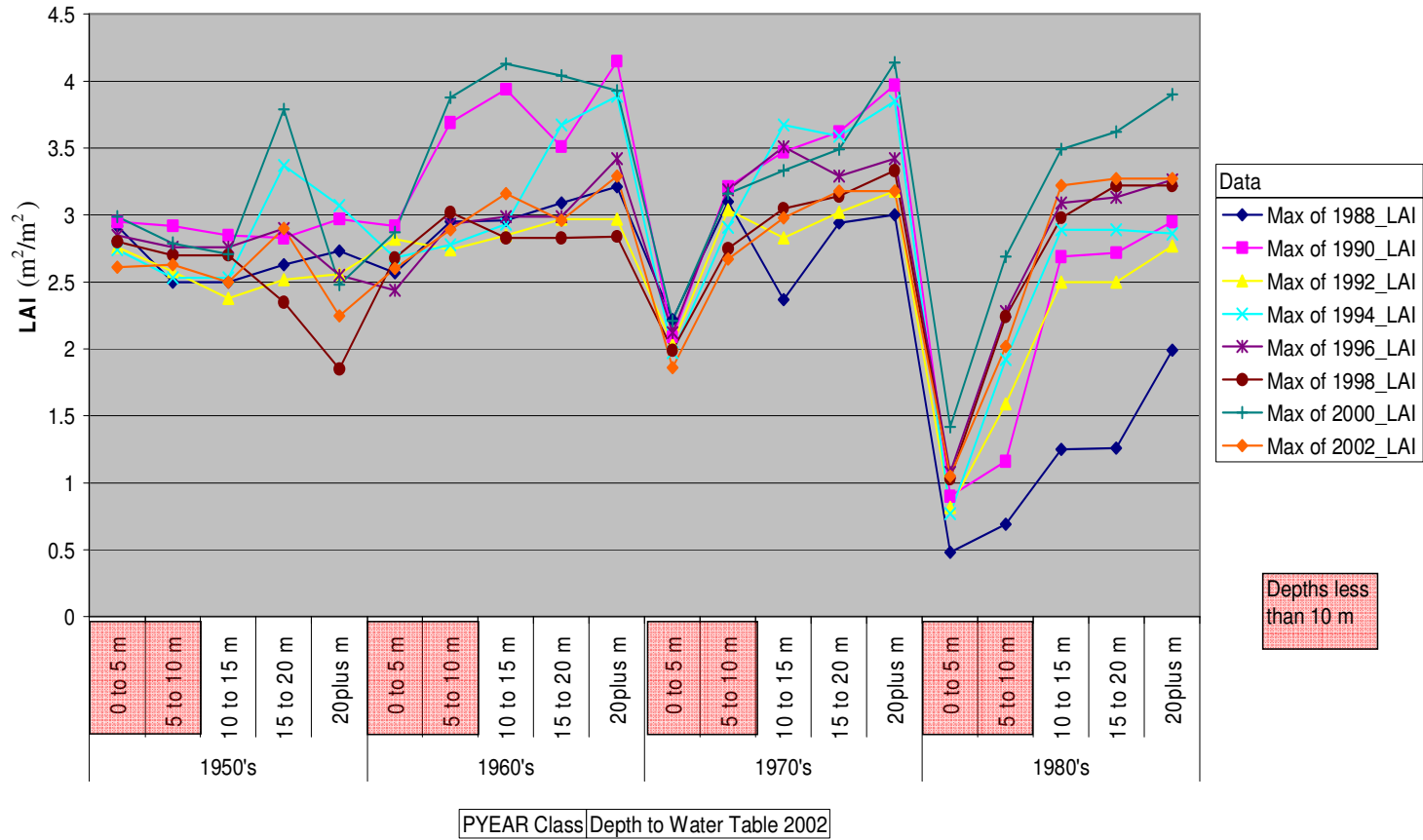


Figure 61. Maximum LAI expressed on Gngangara Mound in relation to depth to water table and Planting year's class

The data in Figure 61 is for the entire Gngangara Mound. At any one time there would have been recent thinning which would have reduced LAI for those stands there would have still been other stands that would have reached their maximum LAI.

The pattern of maximum expressed LAI in Figure 61 suggests that LAI stand growth is repressed on shallow ground water areas less than 10 metres at ages below 20 years. A shallow depth to groundwater below 10 metres is inhibiting growth due to less unsaturated soil volume being available to the trees at ages below 20. This is despite many of these young

stands being at a far higher stocking density which would normally mean a greater growth of LAI (Figure 62).

The difference in maximum LAI recorded at lower and higher depths to the water table declines with increasing age. However, there are still perceivable declines at lower depths to water table in the 1960s age class. The effect in the 1950s age class is not seen probably because by the time the stands have reached 2002 they have an average stocking of only 126 stems/ha and it is likely these stands are not fully occupying the site. Large gaps between the trees at this low stocking will never be able to be occupied. Hence they are not able to fully express maximum site LAI. The difference in LAI between different depths to water table as seen in younger stands is then hidden for this age class group.

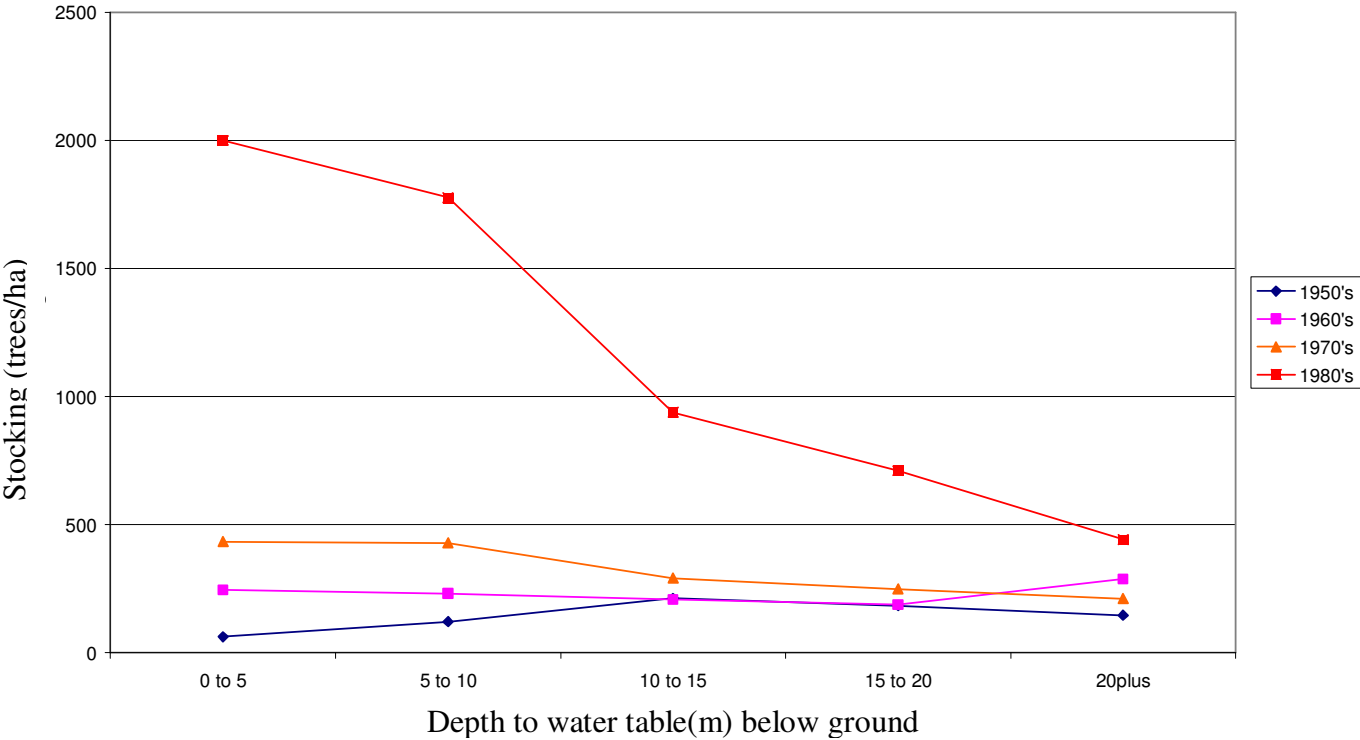


Figure 62. Area weighted average stockings for age classes of *P. pinaster* Aiton for different depths to water table in 2002 (Weighting by area has been carried out to achieve a consistent average per hectare value)

Benyon (2002) contended that there was a high degree of uncertainty in our knowledge of rates of groundwater use by plantations for sites with water tables below 10 metres from the surface. Benyon (2002) also contended that due to these gaps in our knowledge water use rates on such sites are likely to be accurate only to within hundreds of millimetres per year.

Unlike, Benyon's (2002) observations which were that maximum LAI was highly variable for the green triangle, the maximum LAI on Gngangara Mound is in a narrow range for closed canopy stands and not highly variable. In fact maximum LAI is less on shallower depths to water. If these stands on shallow water tables were using ground water it is logical to assume that that they would have higher LAI's based on Benyon's (2002) observations. Benyon and Doody (2004) state that "it is evident some plantations not using groundwater were able to maintain a relatively high LAI ( $\sim 3$  to  $4 \text{ m}^2/\text{m}^2$ ) through summer under conditions of mild drought stress" (p. 18). Benyon and Doody (2004) suggested that during the dry conditions over summer the trees controlled their transpiration rates by stomatal closure. Benyon and Doody (2004) further suggest that if plantations with a similar LAI were accessing groundwater they would have been able to maintain higher transpiration rates over summer through greater stomatal conductance. Gngangara mound and the green triangle climate are similar with a Mediterranean climate with long dry summers and wet winters.

All of the evidence presented on growth rates and water stress outlined above strongly suggests that the *P. pinaster* Aiton plantations on the Gngangara Mound are not using groundwater even when they would appear to have access to it. In fact shallow depth to groundwater is inhibiting growth. This is probably because there is less unsaturated soil volume available and hence less total soil water available to trees growing on these sites.

### iii) Groundwater Recharge rates and LAI on the Gngangara Mound for *P. pinaster* Aiton

Young (below 20 years of age) stands of *P. pinaster* Aiton have LAI growth which has a sigmoidal growth pattern on the Gngangara Mound (See Chapter 5). This is probably caused by increasing reductions of water availability. It can then be hypothesized that the water usage is also sigmoidal. It would then follow that the recharge below the young stands with age is a negative sigmoid (Figure 63). That is it mirrors the growth rates of LAI in reverse. There would be an increasing capture of the total rainfall with increasing LAI until it reaches the site maximum LAI and then plateaus. This is significant in that it means that it will be possible to derive an LAI to water recharge relationship by combining the young stand (below 20 years of age) LAI growth and the hypothesised water usage pattern.

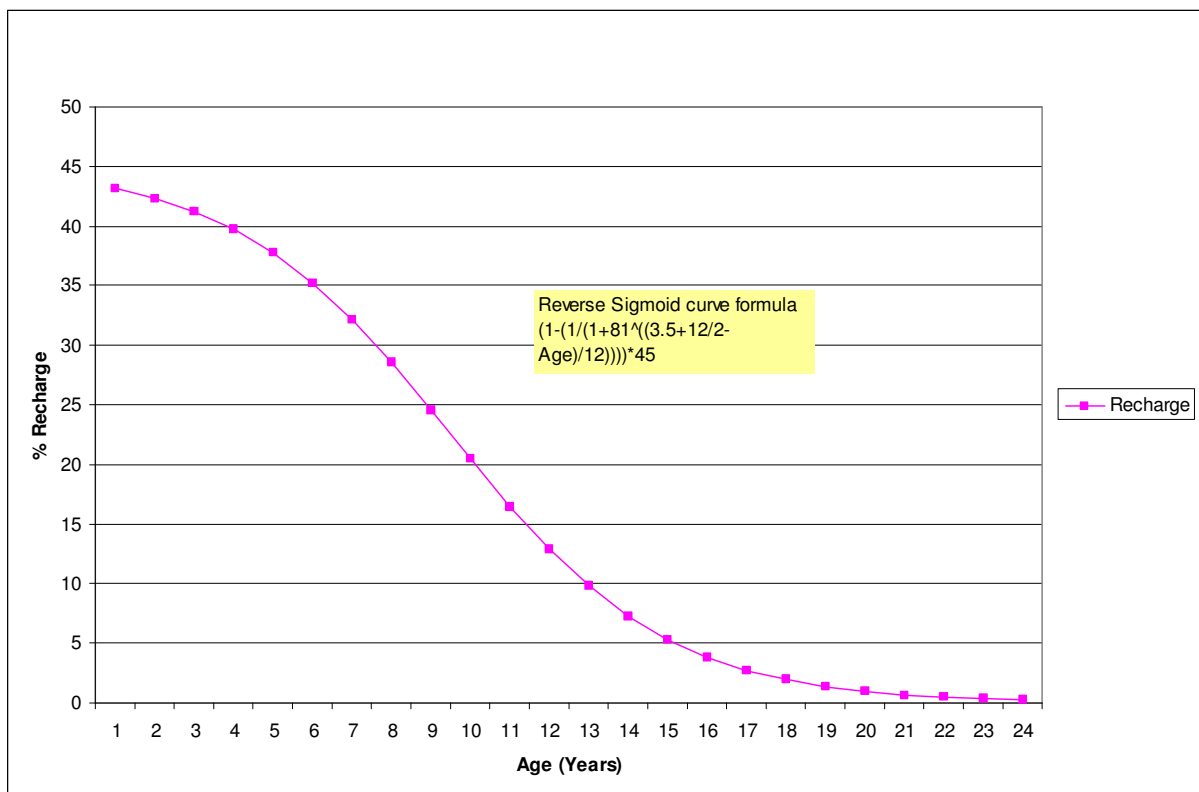


Figure 63. Possible hypothesized recharge to age relationship as derived from young stand (below 20 years of age) LAI growth pattern

This recharge relationship when combined with LAI growth for the same ages of young stands (below 20 years of age) results in a negative linear relationship as shown in Figure 64.

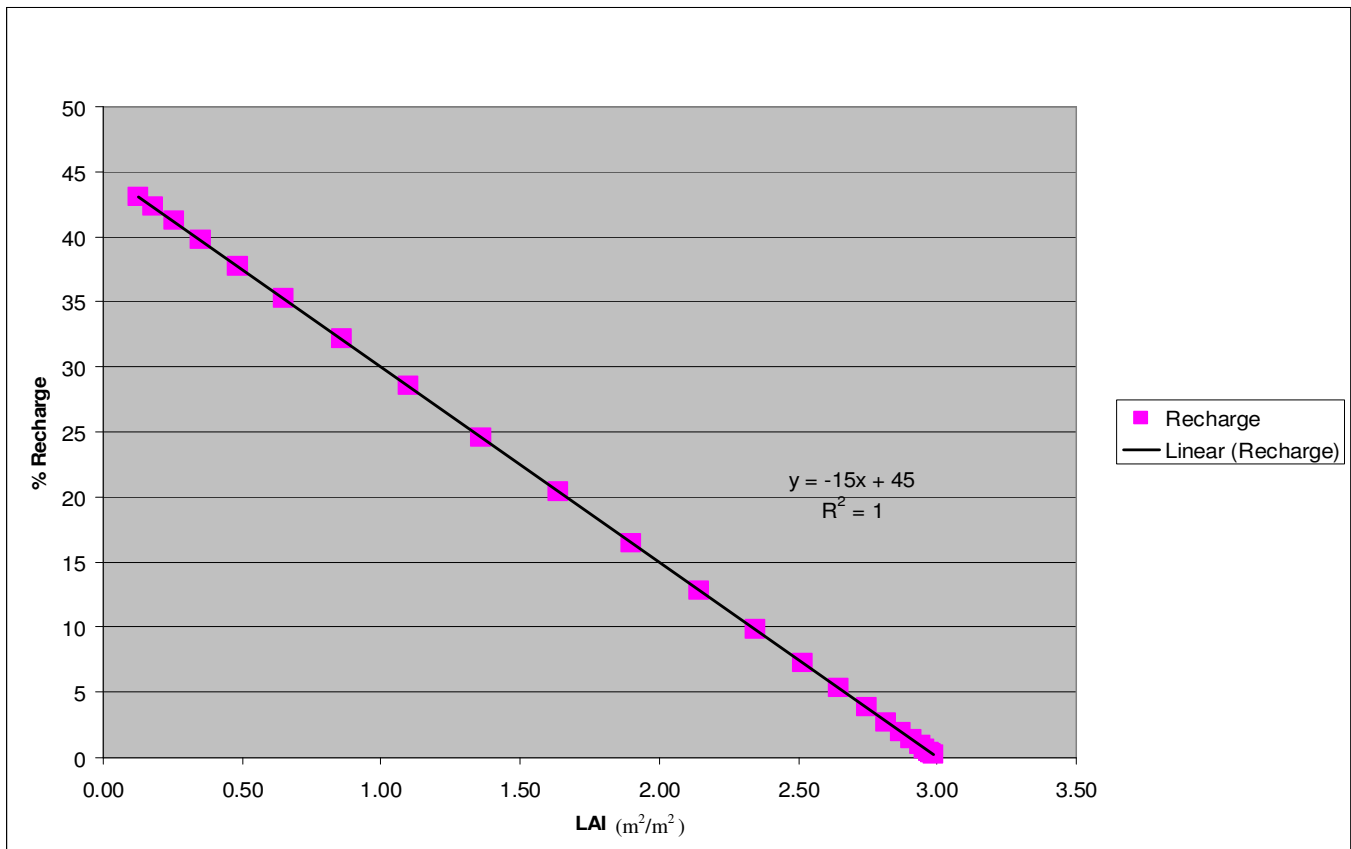


Figure 64. Combination of theorized recharge by age and actual LAI growth for age to produce a LAI to recharge relationship

It differs for the LAI to recharge relationship used in Xu, Canci, Martin, Donnelly and Stokes (2004) which proposes that above LAI  $1.5 \text{ m}^2/\text{m}^2$  there is a complete extinguishment of recharge (Table 6). Xu et. al (2004) come to this conclusion by using the PRAMS model. Xu et. al (2004) also cite the findings of Ellis, Hatton and Nuberg (1999) who found that the site maximum equilibrium LAI for a range of Australian sclerophyll woody vegetation types with an equivalent rainfall and evaporation is  $1.62 \text{ m}^2/\text{m}^2$ .



Table 6. PRAMS recharge categories (Xu, Canci, Martin, Donnelly and Stokes (2004))

		Recharge (mm)	Recharge as a percentage of rainfall	Nominal LAI (m <sup>2</sup> /m <sup>2</sup> )
Pine	Pine High density	0	0	2.75
	Pine med to high	0	0	2.25
	Pine medium	0	0	1.75
	Pine low to medium	65	8	1.25
	Pine low	220	28	0.75
	Pine very low	360	45	>0.5
Banksia	Banksia High density	85	10	1.26
	Banksia medium	135	18	1.08
	Banksia low	300	38	0.66

If total water usage occurs at an LAI of 1.6 in *P. pinaster* Aiton then it is difficult to explain why it continues grow and to double this LAI to 3.3 m<sup>2</sup>/m<sup>2</sup>. It is inconceivable that a plant would double its transpiration and rainfall interception area if it has already reached the limitation of full site water usage.

The use of a recharge relationship developed elsewhere in Australia for comparison also ignores the findings of Petheram et. al. (2000) who found that the data on water use and recharge from Gnangara Mound in Western Australia was significantly different from other places in Australia such that it required additional analysis to recognise its unique characteristics including low water retention sandy soils.

Xu et. al (2004) also found that there is a significant over prediction for water uptake by pines on sites with shallow depth to water tables when the LAI was greater than 2 m<sup>2</sup>/m<sup>2</sup> using the WAVES model. Xu et. al (2004) describe this deficiency as being caused by the assumption in WAVES that these stands were able to access saturated groundwater. Xu et. al (2004) found that the modelled “resultant large water table declines were not consistent with the observation bore data” (p. 24). Xu et. al (2004) also find difficulty in WAVES simulations for the native woodland as a part of model calibration. Calibrated nominal LAI values for the medium density Banksia are at 1.08 m<sup>2</sup>/m<sup>2</sup> and this is well over the range of 0.75-0.85 m<sup>2</sup>/m<sup>2</sup> used in PRAMS.

All of these issues put some doubt in the applicability and reliability of the PRAMS modelling process used to predict LAI to water recharge.

There is a strong relationship between water usage and growth and a sigmoidal pattern of LAI growth in young stands (<20 years old) (Figure 42) that have not been thinned. It therefore can be contended that on this basis the pattern is most likely to be as hypothesised in Figure 65 because this is able to explain the LAI to age pattern for young stands (<20 years old) whereas a full extinguishment at LAI  $1.5 \text{ m}^2/\text{m}^2$  is not able to explain the ongoing LAI growth to  $3.3 \text{ m}^2/\text{m}^2$ .

Sharma, Barron and Craig (1991), Farrington & Bartle (1991) and Butcher (1979) also found that for sites of high pine LAI (approx  $2.5 \text{ m}^2/\text{m}^2$ ) water recharge was less than 8%, 15%, and 8% respectively. This does not supports the conclusion that there an extinguishment of recharge for LAI greater than  $1.5 \text{ m}^2/\text{m}^2$  assumed in PRAMS. These values of approximately 8% are closer to that described by the hypothesis of a linear relationship between LAI and water recharge as shown in Figure 64.

If the hypothesis of a linear relationship between LAI and water recharge was correct then both the *Banksia sp.* and *P. pinaster* Aiton recharge rates may have been underestimated in PRAMS. Components of the total water balance such as the private water usage amount are not accurately measured and are a guesstimate. Give this it is possible that the calibration calculations that rely on whole system balance in PRAMS are not correct.

The exact usage of groundwater through private extraction on the Gngangara Mound is unknown but estimated at 220GL per annum (representing approximately 50% of total usage) and this could be an underestimate. There are also large differences of 100GL per annum in 9 out of the 23 years between 1980 and 2003 reported in Vogwill, McHugh, O'Boy and Yu (2008), between the measured water storage decline and PRAMS modelled decline on

Gnangara Mound. This substantial difference is far greater than has been claimed for the water usage of the Gnangara Mound pine plantations.

Vogwill, McHugh, O'Boy and Yu (2008) also state that PRAMS modelling indicates “high-density native vegetation, particularly Banksia woodland areas, are heavy water users” (p. 33). Vogwill, McHugh, O'Boy and Yu (2008) found that the model is very sensitive to native vegetation density because of the very broad distribution of native vegetation on the mound. Xu et. al (2004) report “there is also some uncertainty in the estimated leaf area index for native woodland” (p. 27) on Gnangara Mound. If the native vegetation density has been incorrectly described then this too could be a significant source of error in prescribing the relative portions of water use in the whole system water balance.

Dr. Ramsis Salama former Senior Principal Research Scientist and Project Leader CSIRO Land and Water, Australia is highly critical of PRAMS (Salama 2008).

Salama (2008) states that “according to Vogwill (2004) a large number of problems and difficulties have been encountered in the climate modelling including lack of data to construct “representative” sequences from existing data, uncertain inter-relationships between climatic stations, and current inability to produce “manufactured” data due to the nature and detail of data requirements” (p. 1) Salama (2008) further contends in most cases the large numbers of parameters needed for modelling are unknown and must be estimated as there is no data for the recharge response units. For example soil characteristics are poorly defined, LAI are not known for the different vegetation types and recharge characteristics are “a big mystery” (p. 1) (Salama 2008). Salama (2008) is also critical that “because the models calibrations are based on trial and error and in most cases the sensitivity of any of the parameters is dependent on so many variables that in the end there will be no relationship between what is true and what is creation” (p. 1). Salama (2008) concludes that the “PRAMS model is not suitable to

understand or predict impact to the level required for fixing allocation limits or to investigate the dominant factors that are influencing declines” (p. 1).

There is a further important potential source of error in the PRAMS model. It is dependent on the base year used for calibration. The net total impact of pines includes an increase of water tables depth due to the original clearing of native vegetation, which would have a rebound period. A base year of 1979 is used in PRAMS modelling, such as that used by Department of Environment (2005). The usage of 1979 as a base year for comparisons in looking at water level impacts will be influenced by the impact of a large clearing surge in water table caused by prior clearing for establishment of pine. Figure 64 quite clearly shows there was significant clearing that was carried out prior to planting pines before 1979.

The impact of clearing for pines was assessed by constructing a cross section through the Pinjar area and graphing the water table level results for 1979, 1988 and 2002 (Figure 66).

Figure 68 shows that the water table increased from 1979 to 1988 then receded for a significant portion of this cross section. The net impact of pine management including clearing for establishment therefore needs to be taken into account. Significant errors because water tables rose upwards of 4 metres directly after clearing at some monitor sites could be made if 1979 is use as a base comparison year because there may be a decline from a higher base caused by clearing for pines in this area. Prescribing all this loss to other factors may be incorrect. Indeed the water table rise caused by clearing of native vegetation prior to pine establishment may make calibration of PRAMS extremely difficult as there is an insufficient set of data prior to 1979 when major water table measurements commenced regularly.

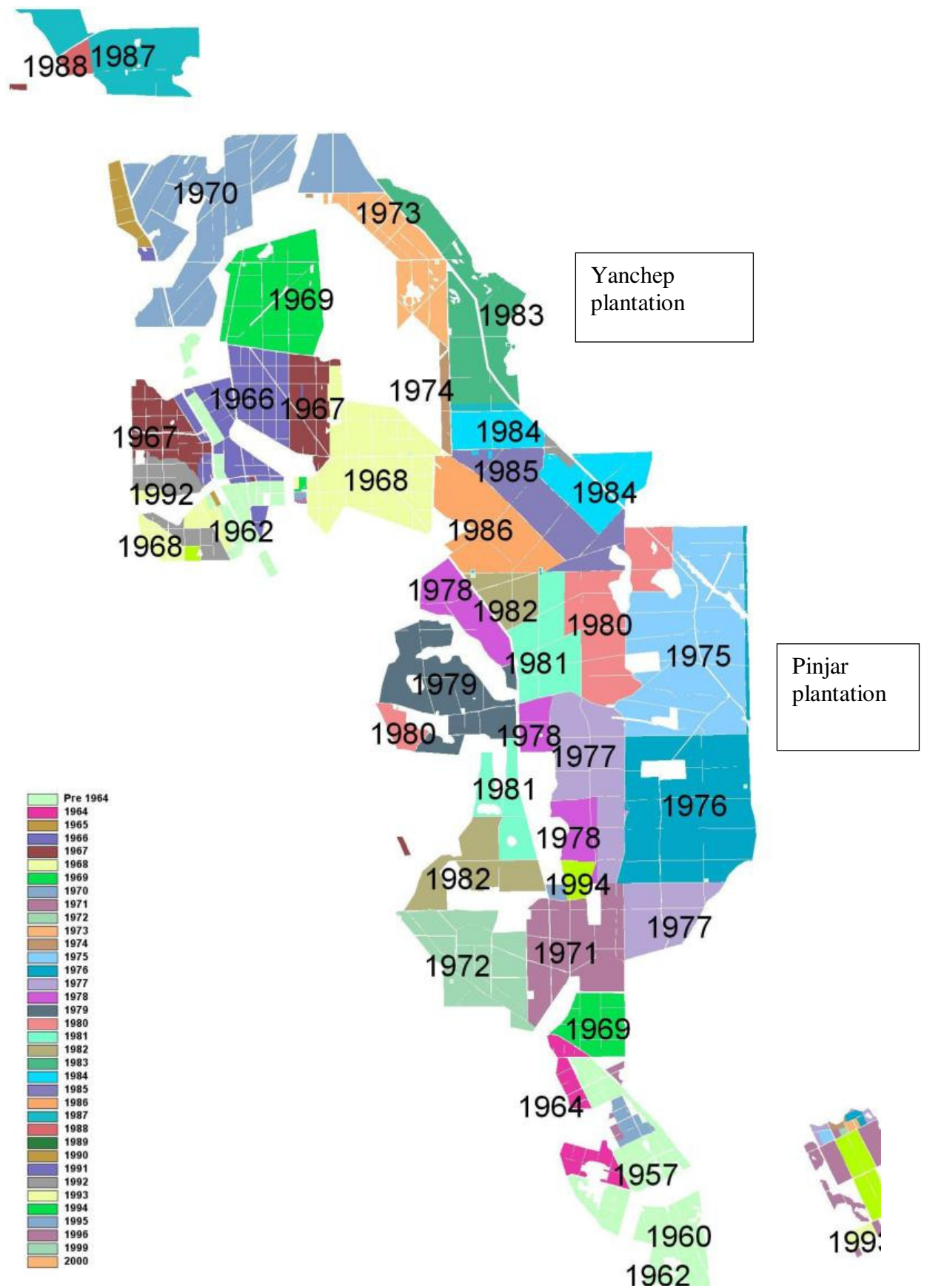


Figure 65. Planting years in Pinjar and Yanchep plantations

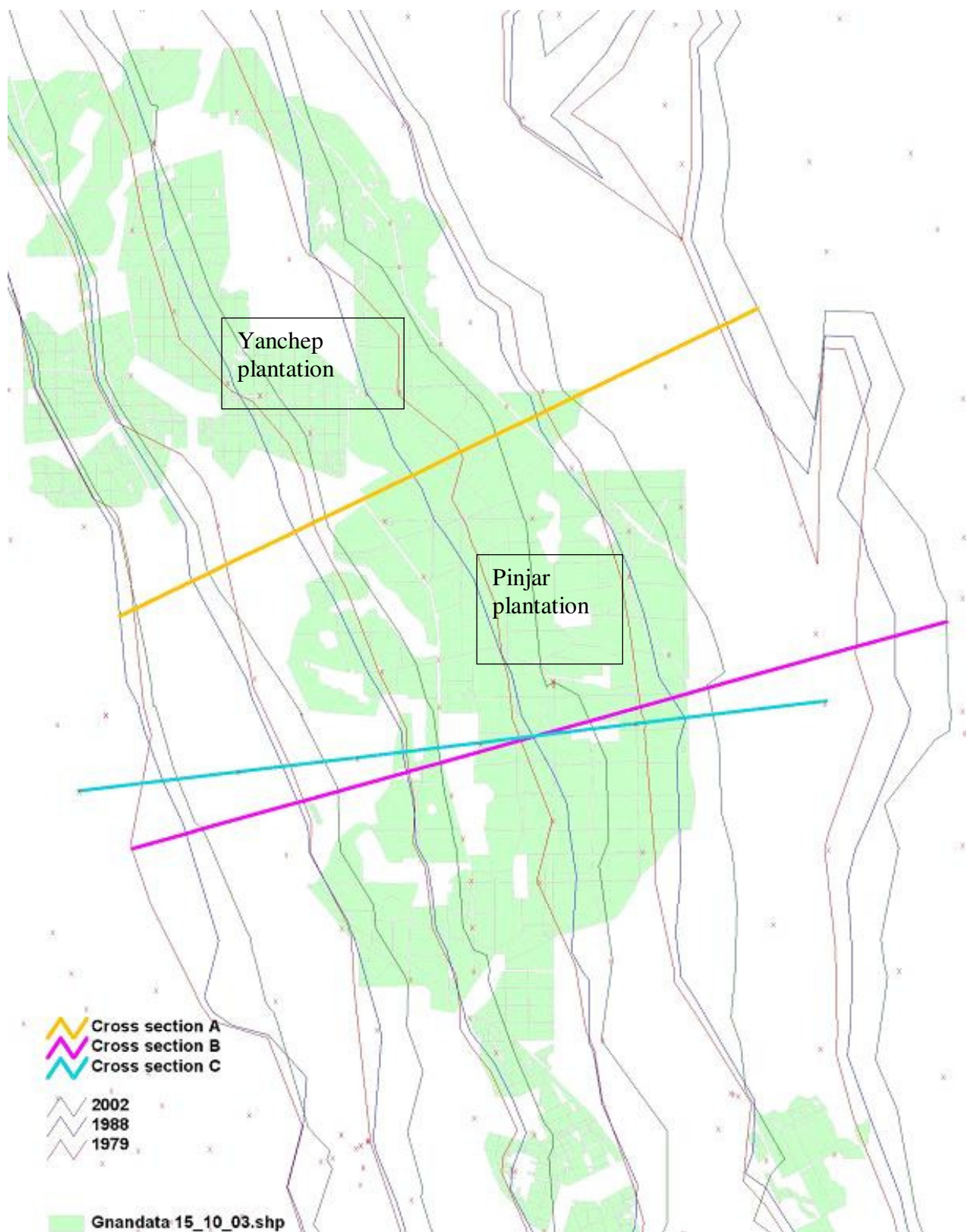


Figure 66. Cross sections and water table levels over time

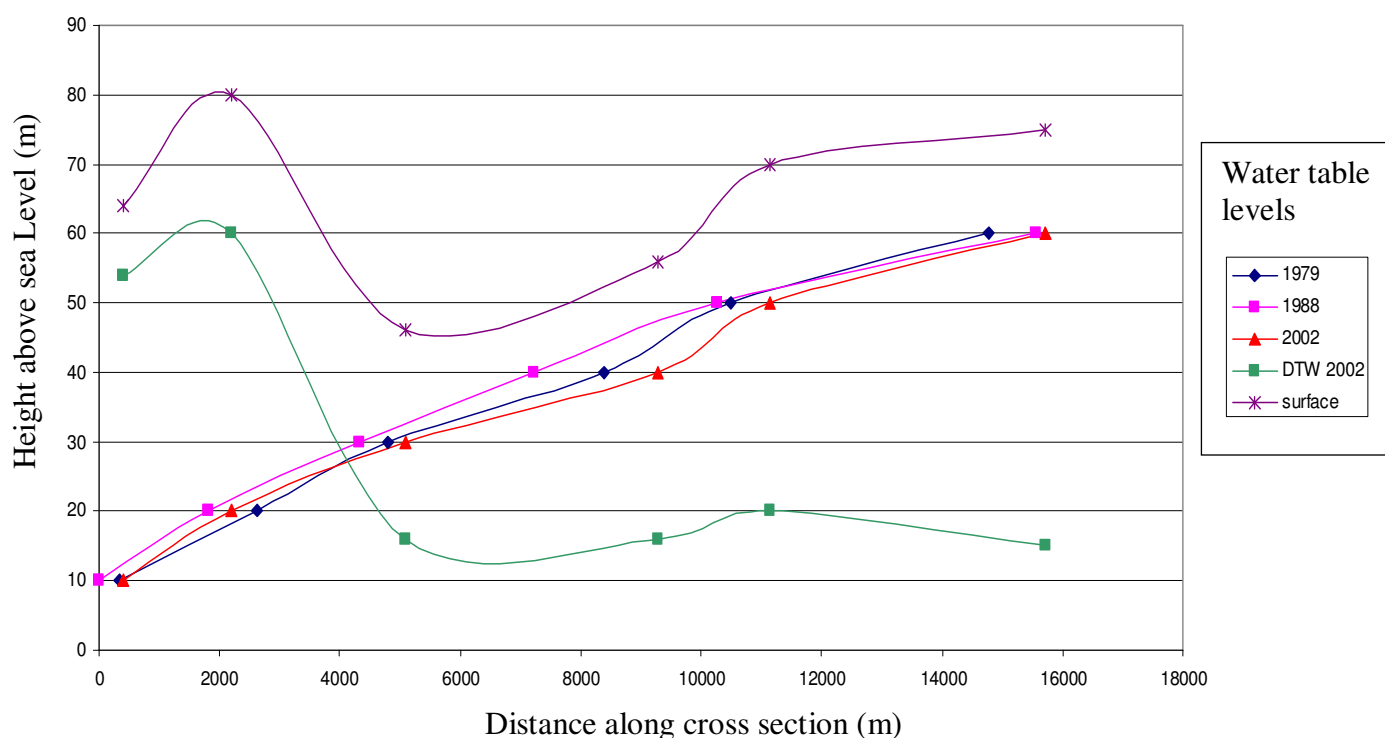


Figure 67. Cross section A water table levels in 1979, 1988, 2002 and depth to water table in 2002 and surface elevation above sea level (water levels as provided by Water and Rivers commission)

Water recharge percentage of *P. pinaster* Aiton using hypothesised linear relationship (Figure 64) to LAI and PRAMS recharge to LAI relationship (Table 6) where calculated to compare the different theorised recharge to LAI relationships.

Table 7 and Figure 68 show a relative difference of 23 GL recharge in 2008 between an equivalent area of Banksia to that of the *P. pinaster* Aiton if a linear relationship of LAI to recharge is assumed. Whereas using the PRAMS recharge relationship it is only 11GL in 2008. Water recharge amounts of Gnangara mound *P. pinaster* Aiton and Banksia using hypothesised linear relationship to LAI are significantly greater than the PRAMS recharge to LAI relationship (Figure 68).

Table 7 Water recharge percentage of *P. pinaster* Aiton using hypothesised linear relationship (Figure 65) to LAI and PRAMS recharge to LAI relationship (Table 6).

Year	1988	1996	1998	2002	2008	Banksia
Average LAI m <sup>2</sup> /m <sup>2</sup>	1.23	1.99	1.58	1.78	1.57	1.08
Linear recharge to LAI hypothesis						
Recharge GL	46.3	26.4	37.2	31.9	37.4	50.3
Percentage recharge	26.6	15.2	21.3	18.3	21.5	28.8
PRAMS recharge to LAI relationship						
Recharge GL	21.5	15.2	16.8	20.7	18.5	29.5
Percentage recharge	12.3	8.7	9.6	11.9	10.6	16.9

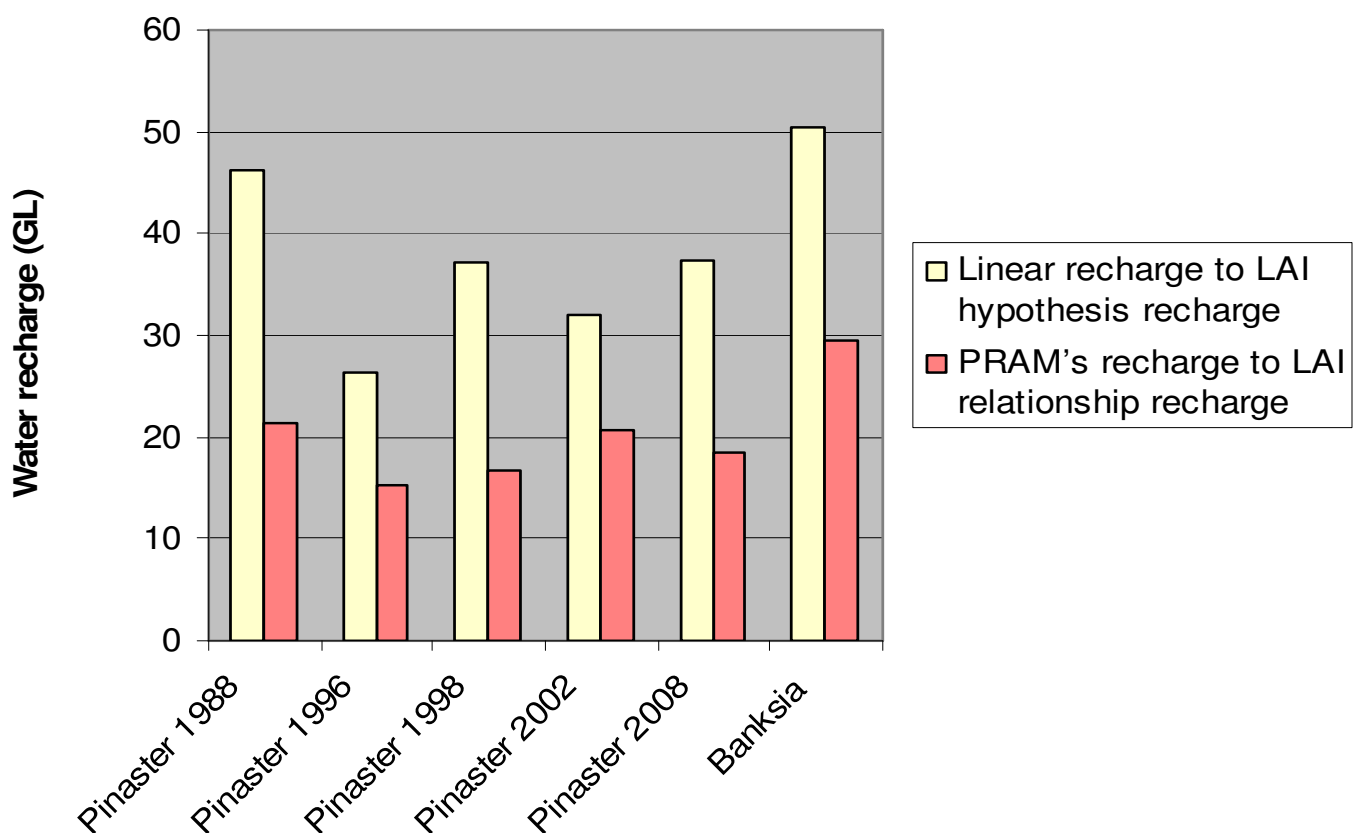


Figure 68. Water recharge amounts of Gngara mound *P. pinaster* Aiton and Banksia using hypothesised linear relationship to LAI and PRAMS recharge to LAI relationship

#### iv) Using LAI as a substitute for water recharge

Given some uncertainty in the LAI to water recharge relationship its use directly in the model could potentially have introduced unquantifiable errors, which would add additional uncertainty to the model. It was therefore decided not to add in a water recharge relationship



directly into the model to be constructed to test different harvesting regimes. Fortunately, LAI has a strong inverse relation to water recharge. Consequently, LAI minimization within a model however would have the same effect as maximizing the water recharge.

If required any water relationship to LAI can then be added on to the results of scenarios without adding additional sources of potential error. Provided the same LAI to water recharge relationship is used for all the scenarios and a comparison area of *Banksia sp.* then the best scenario for water can be still found. For example, if a scenario has a much lower LAI because of different silvicultural choices, but still maintains an ability to meet the contractual timber volume demands, then this would be a better choice when trying to achieve a greater water recharge outcome than another scenario with a higher LAI. There will be however, be some significant remaining uncertainty of the exact quantity of the water recharge outcome. The consequence of this will be that it will only be possible to compare scenario outcomes and rank them from best to worst in regards to water outcome rather than be definitive in exact water recharge amounts achieved.

It was decided to use both the linear hypothesised LAI to recharge relationship and the PRAMS LAI to water recharge relationship on the model result with a LAI minimisation scenario. A sensitivity analysis of the water outcome could then be undertaken by varying the LAI to water recharge relationship factors. Each scenario and their rankings against each other can be compared for both LAI to water recharge relationships.

Lower LAI with volumes met	= Better water outcome within constraints
Higher LAI with volumes met	= Poorer water outcome within constraints

## 7. Harvesting regimes

### i) Linear programming use in forest management

Paradis (2003) states “forest management planning is all about decisions” (p. 1). To make these decisions requires the collection of vast amounts of data and its analysis. Computer models are a credible and popular approach used to assist in the decision support for these planning issues (Reynolds and Schmodlt 2006). They allow the planners to make better management plans. Systems have been designed to solve decision making problems on which areas to harvest at what time, what volume to cut and how to cut up the trees into logs to meet a demand level.

Martell, Gunn and Weintraub (1998) contend that forest management has evolved from relatively simple decision making requirements for simple stand rotation decisions to one now requiring production decisions on large forest management units while attempting to reconcile conflicting demands for non timber values. Martell, Gunn and Weintraub (1998) suggest it is not surprising then that forestry continues to be a rich source of problems that push foresters and operation researchers to the limits of their capability. In addition, they suggest that crucial regional differences cannot be ignored when discussing operations research and forestry and these influence the models and the modelling approaches that have been developed.

Leach (2003) describes linear programming as a procedure to set up a mathematical model of a process consisting of a set of simultaneous equations that uses matrix algebra to obtain the solution that maximizes the profitability of the process. In raw material processes such as forest resource planning the problem is to find the solution that gives positive values for all the variables and maximizes the profit subject to constraints.

Processes that are inherently non linear, where outputs are not proportional to inputs are not solvable using linear programming (Leach 2003). “Linear programming has been applied many times in the forest industry to optimise log allocation” (Leach 2003). Often there are simply too many variables in processes for a human being to determine the best way to operate at the most profit. Leach (2003) further suggests that it is important that linear programming be applied by people familiar with the process being optimised rather than theorists who only know the mathematics. In particular, Leach (2003) points out it is the handling of the human factors and the support of management that determine how successful the application of linear programming is to solving problems.

A forest estate model is described as a model used for planning the management of aggregates of forest stands or forest estates (FOLPI user guide 2002). The Gngangara Mound has 400 stands in 2008 recognized by Forest Products Commission and thus the application of an estate planning model is essential for intensive management.

Epstein et. al. (1999) describes their use of linear programming. Epstein et. al. (1999) were able to increase net revenues to the companies that implemented them by 5 to 8 percent over the usual manual processes.

FOLPI (Forestry Oriented Linear Programming Interpreter) was developed by the New Zealand Forest Research Institute in 1984 to solve forest estate modelling problems. It is a Microsoft DOS (Disk Operating System) based system that has been superseded by newer software packages like “Woodstock” by Remsoft (Remsoft 2004).

Lindo (2003a) describes one of the most useful attributes of a system set up for a Chilean forest company using “What’s Best” as “allowing easy investigation of a number of different

scenarios before making critical decisions” (p. 1). An additional benefit was that it provided a better understanding of the problem they faced.

LINGO is being used to help in decision making in forest harvesting of the Siberian timberlands for Russia (Lindo 2003b).

Church et. al. (2000) observe that the USDA “forest service analysts have long relied on computer based modelling, especially linear programming to address complex problems” ( P. 248). One of the weaknesses however of linear programming is the general lack of the spatial dimension in the decision making process. The absence of this attribute means that plans cannot be seen visually to aid in the analysis of the problem (Church et. al. 2000).

Fortunately, the Forest Products Commission has a Geographical Information System (GIS) which allows this special dimension to be analysed. The stands attributes entered into linear programming retain a link that can be used to recreate the optimised solution into a visual presentation. In this way, a visual analysis of the solutions provided by optimisation can be audited and more readily understood.

Guignard, Choonho and Speilberg (1998) describe a problem that can occur with timber harvesting systems that are modelled with mixed integer programming. They can become very large and difficult to solve with commercial mixed integer program codes. “CPLEX” is one of the software packages that can overcome some of these problems as it is able to handle large mixed integer problems with undue processing time(Guignard et. al. 1998).

Riddell and McLarin (2003) report that Forestry Tasmania have used Remsoft's “Woodstock” and an optimiser called “Mosek” to provide a solution to the mathematical difficulties they faced with their large coupe based, long timeframe model that commonly available linear

programs could not cope with. It also has a spatial extension that can be added to enable GIS application of the optimised solution (Riddell and McLarin 2003).

## **ii) Gngangara Mound model**

The ultimate aim of the Gngangara Mound model developed was to provide a high level decision support tool that could effectively evaluate the relationship between the water recharge outcome and timber production. This approach would allow stakeholders to consider a range of options and select the one that provides the benefit most appropriate to their objectives. The State Agreement Act (Wood Processing (Wesbeam) Agreement Act 2002) contains constraints, which limit the options of timings for stand removal over the period of the contract. To achieve a better water outcome it may be necessary to depart from the contract schedule. An evaluation of what the impacts of a relaxation of these constraints were was therefore required.

The model did require a number of scenarios to test sensitivity to growth rates, recovery percentage of LVL from gross volumes, increasing volume requirements and shorter liquidation periods. Also tested was whether changing the objective to one of minimizing LAI (equivalent to maximizing ground water recharge) would give a significantly different result to that obtained with a maximize volume objective.

A model was developed initially using CPLEX but was later re-written once the Remsoft's Woodstock was available as this was considerably faster in both developing and solving the different scenarios proposed.

## **iii) Model parameters**

There are 400 separate stands of pines identified for *P. pinaster* Aiton on the Gngangara Mound in 2008. These stands each had their own unique values for age, standing volume, LAI, stocking and future growth rate. All stands had a clearfall operation proposed and a

number have varying thinnings proposed. A thinning would involve removing approximately 50% of the volume standing at that time and at clearfall the total removal of all the volume.

The equations required to formulate the problem have the following basic structure:-

Volume removed = % recovery \* Total volume if clearfall or 40% total volume if thinned

It was impractical to return to any one stand in less than 3 years for more timber, because harvesting yields are too small (less than 50 m<sup>3</sup> per hectare) to be commercially viable for logging contractors.

Wood for the Laminated Veneer Lumber plant as prescribed by the State Agreement Act cannot be less than 25 years old and must meet the weighted average age requirement as documented in Appendix 1.

#### **iv) Overall model assumptions**

##### **a) Resource description**

Resource information was extracted from the FPC forest information systems (GIS and Geomaster) and was current as at 20 February 2008.

##### **b) Area**

The total net stocked area modelled represents 17716.7 hectares of *Pinus pinaster* Aiton plantations located in the Gnangara, Pinjar and Yanchep plantations (Table 8).

Table 8 Net stocked area, Source FPC 20 February 2008

<b>Plantation/Region</b>	<b>Net stocked area (hectares)</b>
Gnangara	4,436.32
Pinjar	6,783.54
Yanchep	6,496.84
<b>Total</b>	<b>17,716.70</b>

The area clearfallen from September 2004 to end of 2007 is approximately 2800 ha and there is an area of approx 1320 hectares of firebreaks within the plantation area.

#### c) Age class and harvesting regime

The FPC provided a schedule identifying harvest regimes for individual stands (thinning or clearfall only operations). The current age class and scheduled harvest regime is shown in Figure 69.

#### d) Growth

Standing volume, as measured in individual stands as part of a 2001 inventory program, were used as starting points for determining plantation growth on the Gnangara Mound region. A total of 400 individual stands (standing volumes) were used in the model as the yield table starting points.

The stands were ‘grown on’ from the measured standing volumes at 2001 to 2008 using the specified mean annual increment (MAI) as shown in Table 9.

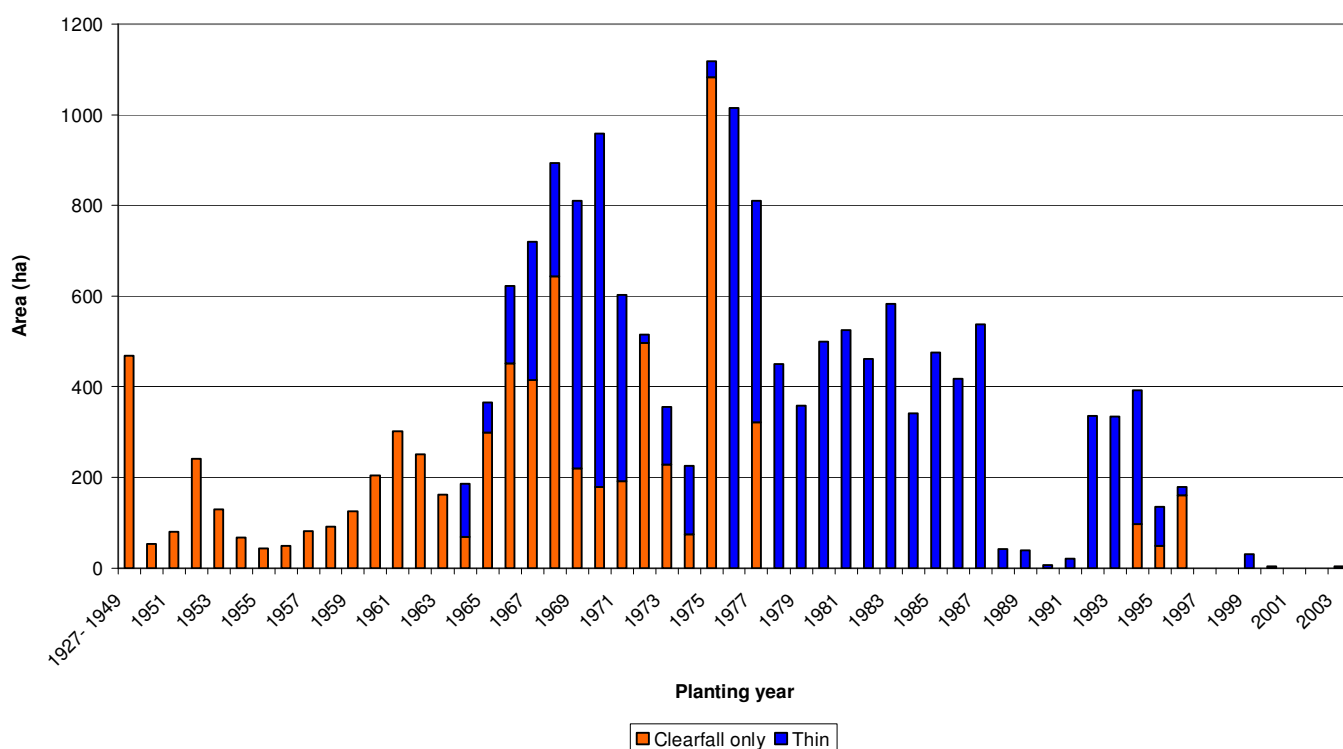


Figure 69. Age class and harvest regime for Gngangara mound plantations, Source FPC 20 February 2008

Where a thinning was completed during this period, it is assumed that 40 percent of the standing volume is removed at the age of thinning as the stocking reductions were 50 percent.

A normal thinning of 50% of the tree stocking removes the smaller trees, which have lesser average volume than the larger trees remaining and hence would have less than half of the total volume.

MAI is assumed to remain constant for all years of the scenarios for both the thinned and clearfall stands.

In order to test sensitivity to growth rates one scenario used the lower growth rates and another the higher growth rates all other scenarios used the normal growth rates (Table 9).

This sensitivity analysis is important because the growth rates achieved from 1992 to 1997 and from 1997 to 2002 were different ( Table 1). There was a decrease in growth rates in the period 1997 to 2002, this could be due to a reduction in the ratio of rainfall to evaporation



recorded (McGrath J., FPC, pers. comm. 2003 unpublished *P. pinaster* Aiton growth research).

The Forest Products Commission has concluded that the average of ten years growth was the most realistic growth rate. However if the reduction of growth that has occurred over the last 5 year is maintained, actual growth rates will be slower than used in the model prediction.

Table 9. Mean annual increment from FPC inventories 1992,1997& 2002 plus sensitivity values for testing at lower and higher rates

	<b>Mean annual increment (m<sup>3</sup>/ha/year)</b>		
<b>Plantation</b>	<b>Normal</b>	<b>Lower growth</b>	<b>Higher growth</b>
Gnangara	6	5	7
Pinjar	8	7	9
Yanchep	8	7	9

#### e) Volume Yield tables

Yield tables were produced to project growth of stands over a 25 year period from 2008 to 2032 for use in the model. The yield tables consisted of a gross standing volume figure for each year was calculated by adding growth rates shown in Table 9 to measured standing volume for each stand in 2002. The stands were also separated into thinning and clearfall only regimes so as to develop the appropriate yield tables (projected growth) used in the model.

#### f) Thinned yield tables

A thinning schedule which identifies timing (age) of future thinning operations for individual stands was provided from the FPC geodatabase schedule system. Stands receive from one to three thinning operations during the projection period. The MAI allocated to the stand is applied to each stand in the thinning schedule.

A 50 percent stocking reduction was prescribed for all thinnings. For all stands in the model, it was then assumed that 40 percent of the standing volume is removed at the scheduled thinning age and the specified MAI remains constant over the projection period.

g) Clearfall only yield tables

For stands of low stocking or older than 45 years that were to receive clearfall only (no thinning) the specified MAI was applied for the length of the projection period.

h) LAI projection

The latest LAI from satellite data available was from February 2007. The stands were grown on taking account of any thinning to 2008 using the formula (see chapter 3):-

$LAI(\text{Growth}) = z0 + a(\text{SPH}) + b(\text{AGE}) + c(\text{SPH} * \text{SPH}) + d(\text{AGE} * \text{AGE})$  parameters

$z0=5.50E-02$ ,  $a=-7.74E-05$ ,  $b=2.58E-03$ ,  $c=2.08E-07$  and  $d=-4.37E-05$ .

This was modified to reflect a maximum LAI of no more than  $3.3 \text{ m}^2/\text{m}^2$ , which is the site maximum for the species (see chapter 5 vii). If negative LAI growth was calculated which occurred for the very old stands it was assumed that no LAI was grown and the previous years LAI value continued. LAI was never reduced in the modelling except when thinning and clearfall occurred. It is possible that LAI reduction occurs in very old age for *P. pinaster* Aiton, but to include negative LAI growth values in the model coefficient calculation would have potentially resulted in spurious outcomes. The area of very old age *P. pinaster* Aiton is small so the consequence of overriding the formula is assumed to be insignificant.

For each thinning LAI was assumed to be reduced by 40 percent the year after thinning was scheduled. LAI was grown on for each year in each stand volume yield table.

i) Yield - Laminated Veneer Lumber (LVL)

LVL recovery factors were applied to the projected standing volumes (Table 10).

Sensitivity to recover percentage of LVL from total gross merchantable volume was tested by running scenarios for 70, 75, 80 and 85 percent maximum recovery.

For all other scenarios where testing for recovery percentage sensitivity was not required the 70 % maximum recovery section of Table 12 was used. This figure was used because it was regarded as the best average recovery consistently achievable given the actual field recovery results to date (Jackson Parker 2008 Forester, Forest Products Commission per comm.).

Table 10 LVL recovery factors

Age	LVL recovery factors			
	70% max	75% max	80% max	85% max
0 to 24	0	0	0	0
25	55	60	65	70
26	56	61	66	71
27	57	62	67	72
28	58	63	68	73
29	59	64	69	74
30	60	65	70	75
31	61	66	71	76
32	62	67	72	77
33	63	68	73	78
34	64	69	74	79
35	65	70	75	80
36	66	71	76	81
37	67	72	77	82
38	68	73	78	83
39	69	74	79	84
40 +	70	75	80	85

#### j) Minimum clearfall harvest age

Given the requirement for laminated veneer lumber created from *P. pinaster* Aiton to be of a particular high quality structural grade a minimum clearfall harvest age of 30 years was assumed in the model.

#### k) Thinning operation intervals

Stands are not allowed to be harvested again for 3 years after a thinning operation. During this 3 year period a stand can not receive a subsequent thinning or clearfall operation.

#### v) Model limitations

The model developed has some limitations because it assumes that:-

- Growth rates don't decline significantly after age 40. The results of inventories in 1992, 1997 and 2002, however, do not indicate any significant reduction in growth past age 40.
- Future growth rates achieved are identical to 1992 to 2002 rates. This is dependent on future rainfall and climate. These growth rate assumptions have been made with the best available data. Sensitivity analysis of growth rates was also undertaken in scenarios (See below).
- LVL recovery from total standing volume is not greater than 70%. Field results to date support this assumption. Sensitivity analysis on this factor was undertaken in scenarios (See below).

These assumptions may produce a result that is a small overestimate of true volumes available because they predict higher growth rates than future climate or rainfall allows or growth rates decline above age 40.

#### vi) Individual scenarios developed

##### a) Sustainable yield of LVL logs to 2026

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Flow of volume to be even from 2008 to 2026.

Comments: Normal growth rates and 70% maximum recovery assumed. This scenario is used as a basis for testing against for all other scenarios. It is the base case and is a major revision of the original 25 year plan prepared in 2001 by the author for the Forest Production Commission. The fourth thinning for example has been removed. This will improve the ability to clearfall areas earlier and consequently reduce the likelihood that individual trees may grow too large to be processed readily by the LVL plant. It reflects the situation at the beginning of 2008, which is different to that assumed in 2001, before the LVL plant was constructed.

As a consequence of these changes this scenario has larger ground water outcomes that originally projected because there would have been fewer stands which would have been clearfelled up until 2008 in the original plan.

The actual clearfelling up until the beginning of 2008 has been 2800 ha. Assuming an average rainfall of 700 mm this would equate to approximately between a total of 9 GL (average stand at half maximum LAI at time of clearfall) and 18 GL (all stands Clearfallen at max LAI) total additional recharge over the period 2005 to 2007.

b) Sustainable yield of LVL logs to 2026 with higher growth rates

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Flow of volume to be even from 2008 to 2026.

Comments: Growth rates increase by 1 m<sup>3</sup> pa MAI to test sensitivity to growth rates. 70% maximum recovery assumed.

c) Sustainable yield of LVL logs to 2026 with lower growth rates

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Flow of volume to be even from 2008 to 2026.

Comments: Growth rates reduced by 1 m<sup>3</sup> pa MAI to test sensitivity to growth rates. 70% maximum recovery assumed.

d) Sustainable yield of LVL logs to 2016

Objective: Maximize total LVL produced from 2008 to 2016.

Constraints: Flow of volume to be even from 2008 to 2026.

Comments: Forced early liquidation of plantation by 10 years earlier than base case. Some stands not totally liquidated due to young age. Normal growth rates and 70% maximum recovery assumed.

e) Sustainable yield of LVL logs to 2021

Objective: Maximize total LVL produced from 2008 to 2021.

Constraints: Flow of volume even from 2008 to 2026.

Comments: Forced early liquidation of plantation by 5 years earlier than base case. Some stands not totally liquidated due to young age. Normal growth rates and 70% maximum recovery assumed.

f) Minimize LAI with 100000 m<sup>3</sup> per annum minimum yield of LVL logs till 2026

Objective: Minimize LAI.

Constraints: Minimum annual volume to be no less than 100000 m<sup>3</sup> for 2008 to 2026. Flow of volume even from 2008 to 2026.

Comments: Normal growth rates and 70% maximum recovery used. The minimize LAI objective is equivalent to an objective of maximised ground water recharge objective.

g) Minimize LAI with liquidation to waste in first year then 100000 m<sup>3</sup> per annum minimum yield of LVL logs till 2026

Objective: Minimize LAI.

Constraints: Volume unconstrained for 2008 allowing for a virtual liquidation to waste volume above 100000 produced in 2008. The minimum annual volume to be no less than 100000 m<sup>3</sup> from 2009 to 2026. The volume output to be even from 2009 to 2026.

Comments: Normal growth rates and 70% maximum recovery assumed. The minimize LAI objective is equivalent to an objective of maximised ground water recharge objective.

h) 130000 m<sup>3</sup> per annum yield of LVL logs for first 5 years then even supply to 2026

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Volume to be 130000 m<sup>3</sup> per annum from 2008 to 2012. Flow of volume even from 2013 to 2026.

Comments: Normal growth rates and 70% maximum recovery assumed. This was used as a part of a series of scenarios to test sensitivity to increasing forced set volumes during 2008 to 2012.

i) 145000 m<sup>3</sup> per annum yield of LVL logs for first 5 years then even supply to 2026

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Volume to be 145000 m<sup>3</sup> per annum from 2008 to 2012. Flow of volume even from 2013 to 2026.

Comments: Normal growth rates and 70% maximum recovery assumed. This was used as a part of a series of scenarios to test sensitivity to increasing forced set volumes during 2008 to 2012.

j) 160000 m<sup>3</sup> per annum yield of LVL logs for first 5 years then even supply to 2026

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Volume to be 160000 m<sup>3</sup> per annum from 2008 to 2012. Flow of volume even from 2013 to 2026.

Comments: Normal growth rates and 70% maximum recovery assumed. This was used as a part of a series of scenarios to test sensitivity to increasing forced set volumes during 2008 to 2012. Each additional increase should increase recharge.

k) 160000 m<sup>3</sup> per annum yield of LVL logs for long as possible

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Volume to be 160000 m<sup>3</sup> for long as possible.

Comments: Normal growth rates and 70% maximum recovery assumed. Scenario run for progressively increasing years until infeasible result obtained. The last feasible result which had the longest period of 160000 m<sup>3</sup> per annum was used for comparison.

l) 175000 m<sup>3</sup> per annum yield of LVL logs for first 5 years then even supply to 2026

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Volume to be 175000 m<sup>3</sup> per annum from 2008 to 2012. Flow of volume to be even from 2013 to 2026.

Comments: Normal growth rates and 70% maximum recovery assumed. This was used as a part of a series of scenarios to test sensitivity to increasing forced set volumes during 2008 to 2012.

m) Forced Clearfall Gngangara

Objective: Maximize total LVL produced from 2008 to 2026.



Constraints: Only Gngangara plantation was prescribed to have its clearfall accelerated to minimise the Gngangara plantation area remaining by end of 2012. Pinjar and Yanchep plantations were not restricted by a forced clearfall to any time frame. Flow of volume even from 2008 to 2026.

Comments: Normal growth rates and 70% maximum recovery assumed. A larger water recharge outcome could be gained by clearfalling as early as possible the areas shallowest to ground water, which are overwhelmingly in Gngangara plantation.

n) Sustainable yield of LVL logs to 2026 and 75 percent max recovery

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Flow of volume to be even from 2008 to 2026.

Comments: Normal growth rates and 75% maximum recovery assumed. Maximum recovery rates increase by 5% to test sensitivity to recovery rates.

o) Sustainable yield of LVL logs to 2026 and 80 percent max recovery

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Flow of volume to be even from 2008 to 2026.

Comments: Normal growth rates and 80% maximum recovery assumed. Maximum recovery rates increase by 10% to test sensitivity to recovery rates.

p) Sustainable yield of LVL logs to 2026 and 85 percent max recovery

Objective: Maximize total LVL produced from 2008 to 2026.

Constraints: Flow of volume to be even from 2008 to 2026.

Comments: Normal growth rates and 85% maximum recovery assumed. Maximum recovery rates increase by 15% to test sensitivity to recovery rates.

q) Sustainable yield of LVL logs to 2029

Objective: Maximize total LVL produced from 2008 to 2029.

Constraints: Flow of volume to be even from 2008 to 2029.

Comments: Normal growth rates and 70% maximum recovery assumed. This scenario simulates what would happen if new planted on leased farmland (1994 to 2007) north maritime pine were not available (There have been significant drought deaths in 5 to 8 year old plantations in the northern maritime pine area from Gingin to Moora).

**vii) Overall outcomes and consequences**

A series of tests of the model output were carried out to test the outcome of model against what is known about the system. For example:-

- Standing volume and area remaining should reduce to near zero in 2027.
- First thinning should occur early in the time period of the model and later in the time period clearfall should be the main harvesting type.
- The largest component of the LVL volume should come from clearfall operations rather than thinnings.

Figures 70, 71, 72, 73 and 74 are examples of the analysis's conducted. Once this was completed, a comparison between scenarios differences was carried out.

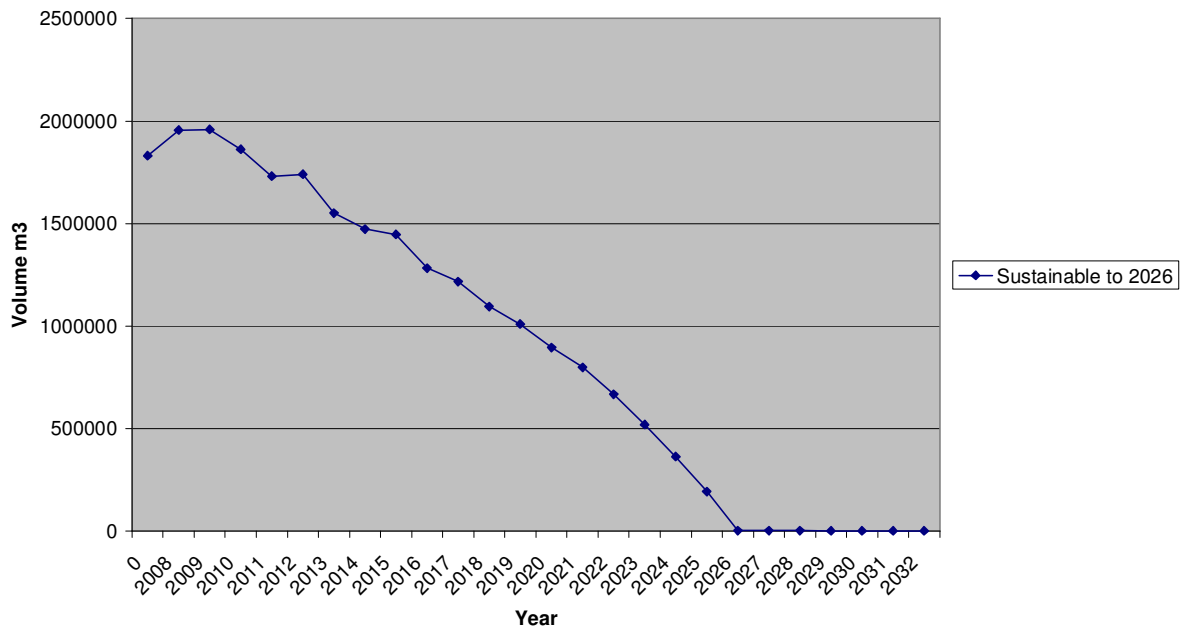


Figure 70. Standing volume outcomes for Sustainable to 2026 scenario

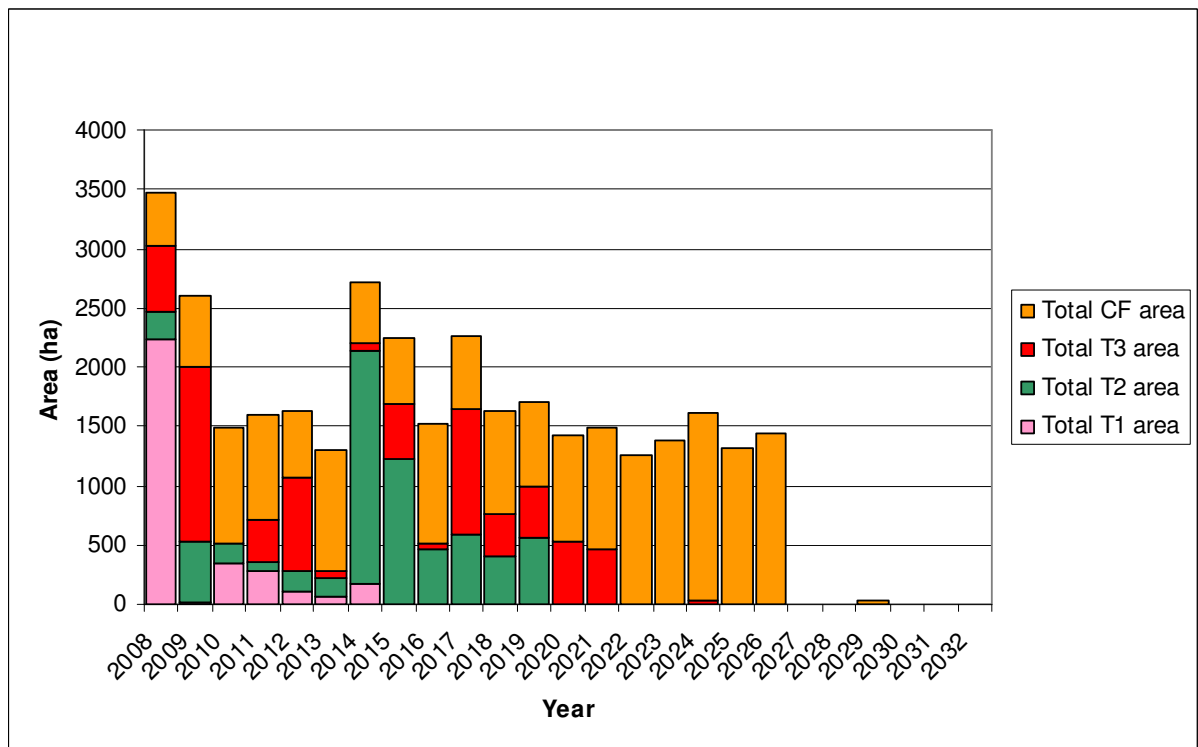


Figure 71. Operational area by type outcomes for Sustainable to 2026 scenario (CF – Clearfall area, T1 first thinning area, T2 second thinning area, T3 third thinning area)

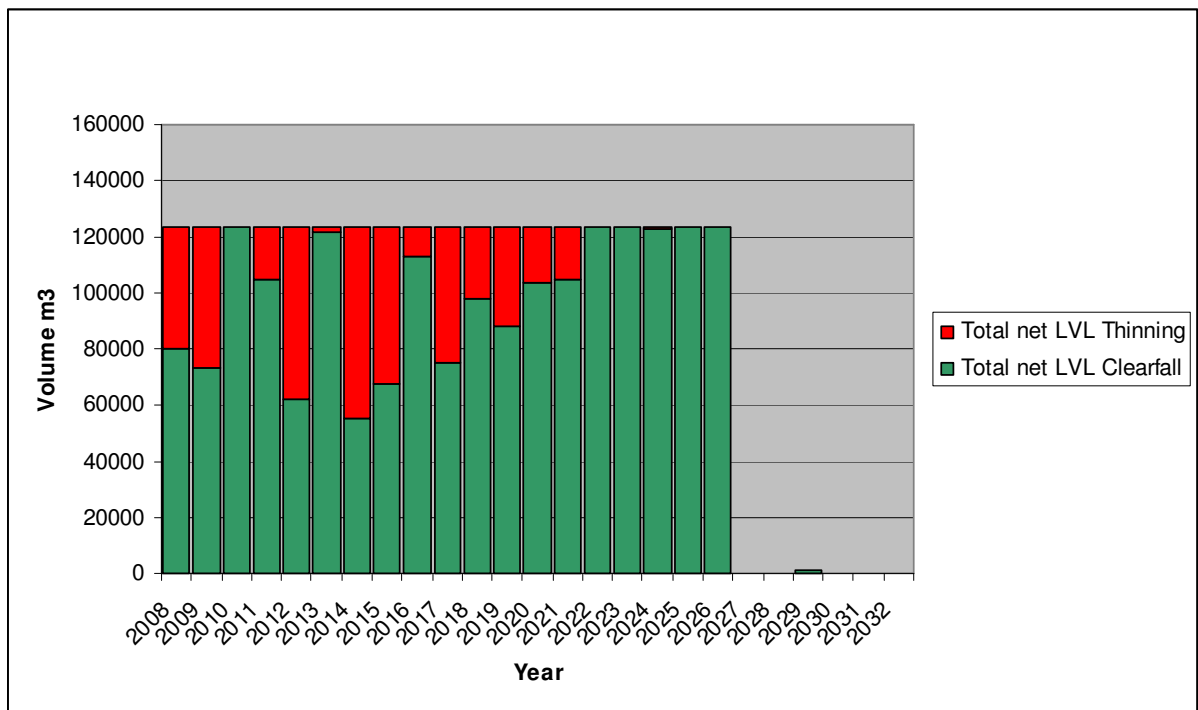


Figure 72. LVL volumes by operational type outcomes for Sustainable to 2026 scenario

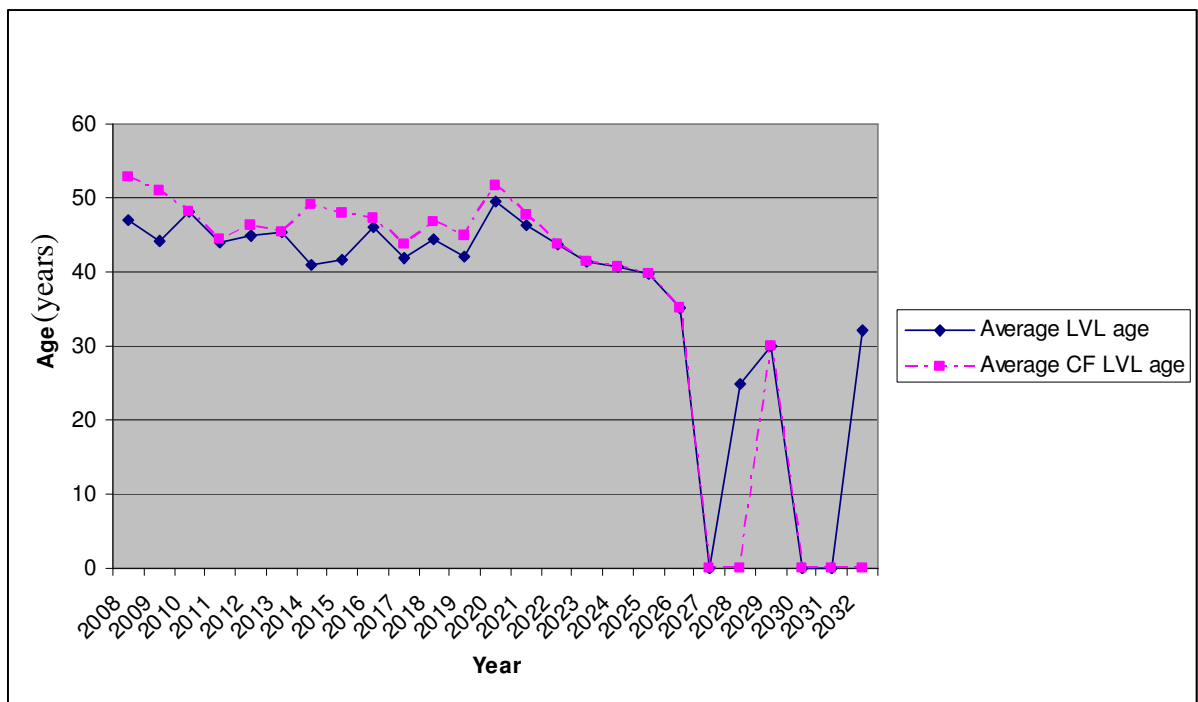


Figure 73. Average LVL age outcomes for Sustainable to 2026 scenario

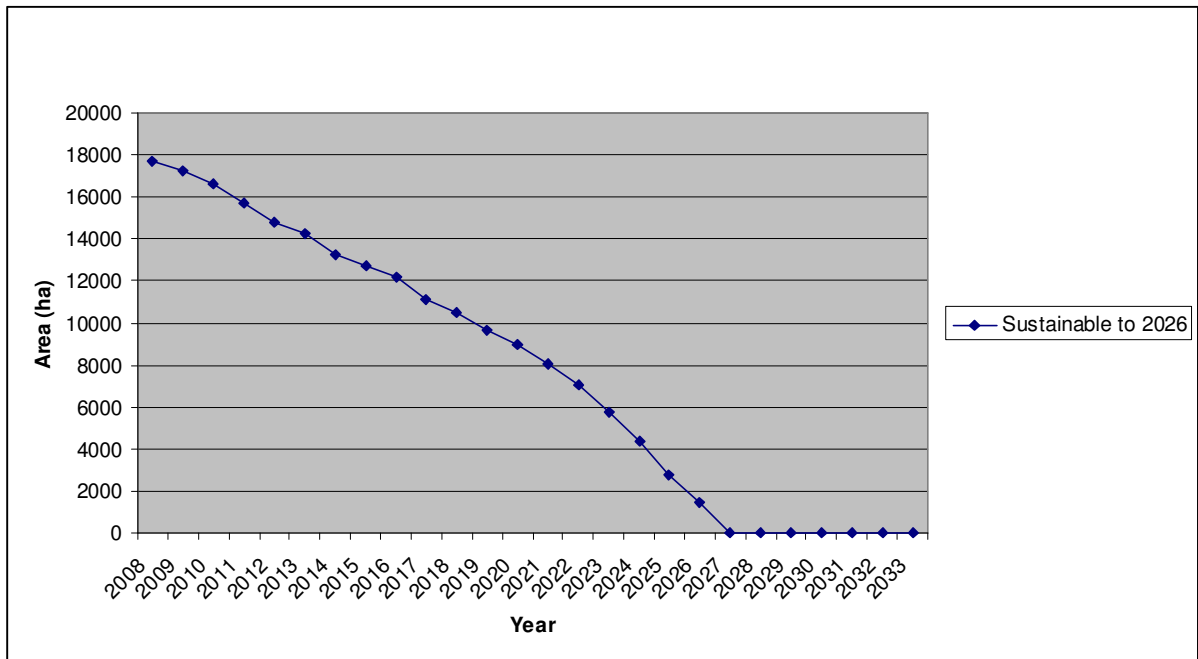


Figure 74. Area remaining standing outcomes for Sustainable to 2026 scenario

Based on the outcomes of the analysis of the model it was seen as a reasonable representation of the Gngangara Mound *P. pinaster* Aiton system and it was liquidating the resource in the required manner (Figure 70 and 74).

The trial runs showed:-

- Standing volume and area remaining did reduce to near zero in 2027.
- First thinning was carried out early in the time period of the model and later in the time period clearfall was the main harvesting type.
- The largest component of the LVL volume did come from clearfall operations rather than thinnings.

#### viii) Sensitivity analysis

A series of scenarios were created and run to test the sensitivity to the major factors affecting the model. Different growth rates, varying recovery percentage of LVL from gross volumes, increasing volume requirements and shorter liquidation periods were subjected to a sensitivity analysis as described below.

a) Growth rates

To test the sensitivity to changes in growth rates prescribed the three scenarios of “Sustainable 2026 lower growth rates”, “Sustainable 2026 higher growth rates” and “Sustainable 2026 normal growth rates” were compared (Table 11).

Table 11. Annual sustainable volume for scenarios testing sensitivity to growth rates prescribed

Annual sustainable volume (m <sup>3</sup> )	
Sustainable 2026 lower growth rates	111721
Sustainable to 2026	123244
Sustainable 2026 higher growth rates	133899

The model found for a 1m<sup>3</sup> MAI growth reduction per annum (which is equivalent to a 13.6% reduction) there is a 9.3% reduction in sustainable volume and for a 1m<sup>3</sup> MAI per annum increase (which is equivalent to a 13.6% increase) there is a 8.6% increase in sustainable volume.

The result shows that the model is moderately sensitive to growth rate applied.

b) Recovery percentage of LVL from gross merchantable volume

To test the sensitivity to the recovery percentage of LVL from gross merchantable volume the four scenarios (Table 12) were compared:-

- Sustainable to 2026 70 percent max recovery,
- Sustainable to 2026 75 percent max recovery,
- Sustainable to 2026 80 percent max recovery and
- Sustainable to 2026 85 percent max recovery

For each 5 percent increase in maximum recovered volume there is a 7.3% increase in sustainable volume. The result shows that the model is sensitive to recovery rate applied.

Table 12. Annual sustainable volume for scenarios in testing sensitivity to increasing recovery percentage of LVL from gross merchantable volume

Annual sustainable volume (m <sup>3</sup> )	
Sustainable to 2026 70 percent max recovery	123244
Sustainable to 2026 75 percent max recovery	132221
Sustainable to 2026 80 percent max recovery	141199
Sustainable to 2026 85 percent max recovery	150178

#### c) Increasing requirements for first 5 years

To test the sensitivity of the model to increasing the wood volume requirements for first 5 years the five scenarios (Table 13) were compared:-

- 130000 m<sup>3</sup> for first 5 years then even supply to 2026,
- 145000 m<sup>3</sup> for first 5 years then even supply to 2026,
- 160000 m<sup>3</sup> for first 5 years then even supply to 2026,
- 175000 m<sup>3</sup> for first 5 years then even supply to 2026 and
- Sustainable to 2026

Table 13. Annual volume for scenarios in testing sensitivity to increasing volume requirements in the first 5 years

	Volume (m <sup>3</sup> )	
	Year 1 to 5	Year 6 on
130000 for first 5 years then even supply to 2026	130000	119520
145000 for first 5 years then even supply to 2026	145000	111108
160000 for first 5 years then even supply to 2026	160000	102462
175000 for first 5 years then even supply to 2026	175000	93421
Sustainable to 2026	123244	123244

Fixing the volume for the first five years to the different scenarios of 130000 m<sup>3</sup>, 145000 m<sup>3</sup>, 160000 m<sup>3</sup> and 175000 m<sup>3</sup> reduces the sustainable annual volume from year six by 3.0, 9.8, 16.9 and 24.2 percent respectively when compared to an even sustainable volume.

The Gngangara Mound constitutes 85% of the area of *P. pinaster* Aiton available and from previous planning exercises by Forest Products Commission produces 90% of the projected LVL volumes. It was assumed that 90% of the requirement of *P. pinaster* Aiton must be met from the Gngangara Mound in the first 22 years as it was not possible to source the younger farmland maritime pine which has been planted on leased farmland between Gingin and Moora north of the Gngangara Mound before this time. The last 3 years may have to be sourced from the new planted maritime pine (*P. pinaster* Aiton) on leased farmland (planting years 1994 to 2007). This would mean that the Gngangara Mound will need to supply 117000 m<sup>3</sup> per annum for the first 22 years to achieve the required contracted volumes.

Within the scenarios of increasing requirements for first 5 years, only the scenarios of 130000 m<sup>3</sup> for first 5 years then even supply to 2026 and Sustainable to 2026 are able to achieve this. This shows there is little latitude to increase the supply much above that sustainable without renegotiating the contract conditions or being prepared to consider financial compensation if the government decided to act unilaterally to increase the annual supply much above the sustainable level.



d) Changed liquidation time

To test the sensitivity to a change in the liquidation time the five scenarios of Sustainable to 2016, Sustainable to 2021, Sustainable to 2026, Sustainable to 2029 and 160000 m<sup>3</sup> for longest feasible time were compared (Table 14).

Maintaining harvesting rates at 160000 m<sup>3</sup> per annum continuously is only feasible until the end of 2016. After that time there is insufficient volume left to maintain that level of production of LVL logs.

Reducing the requirement to provide a sustainable volume until 2016 and to 2021 increases the volume during this period to 29.5 and 12.0 percent respectively above that required to provide a sustainable volume until 2026.

Increasing the requirement to provide a sustainable volume to 2029 decreases the volume during this period to 18.3 percent respectively below that required to provide a sustainable volume until 2026.

Table 14. Annual sustainable volume for scenarios in testing sensitivity to changed liquidation times

Annual sustainable volume (m <sup>3</sup> )	
Sustainable to 2016	159558
Sustainable to 2021	138023
Sustainable to 2026	123244
Sustainable to 2029	100698

e) Forcing Gngangara plantation to be liquidated in 5 years

To test the sensitivity to forcing an early liquidation of Gngangara the scenarios of Forced Clearfall Gngangara by year 2013 and Sustainable to 2026 were compared (Table 15 and Figure 75).

Table 15. Annual sustainable volume for scenarios in testing sensitivity to forcing Gngangara plantation to be liquidated in the first 5 years versus not doing so

Annual sustainable volume (m <sup>3</sup> )	
Forced CF Gngangara	123048
Sustainable to 2026	123244

Table 16 shows there is a difference of only 196 m<sup>3</sup> per annum or 0.16 percent, which is negligible. This demonstrates that the maximum optimum annual volume is not significantly affected by a forced early clearfall of the Gngangara plantation. This is a logical result as Gngangara is the slowest growing and on average older plantation than Pinjar or Yanchep.

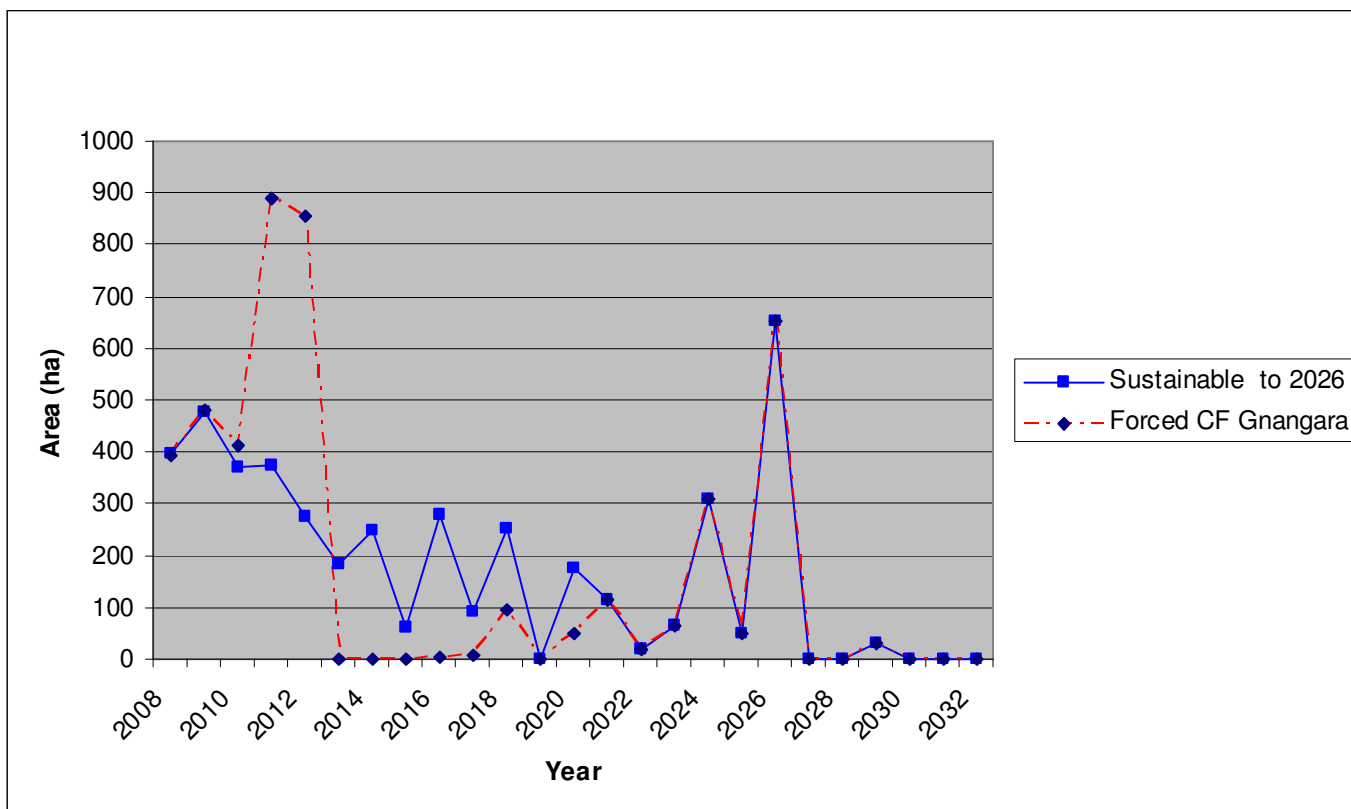


Figure 75. Difference in Area clearfallen in Gngangara plantation between scenarios Forced CF Gngangara and Sustainable to 2026

#### ix) Minimizing LAI

To test the difference of having an objective of minimizing LAI rather than achieving a maximizing of volume the scenarios of :-

- Minimize LAI with 100000 m<sup>3</sup> minimum till 2026,
- Minimize LAI with liquidated to waste in first year then 100000 m<sup>3</sup> minimum till 2026,
- Sustained 2026

were compared for both total merchantable LVL volume and LAI outcome (Table 16 and Figure 76).

The scenario that minimizes LAI with liquidation to waste in the first year then 100000 m<sup>3</sup> per annum minimum until 2026 results in the model cutting 315447 m<sup>3</sup> in the first year and then 100000 m<sup>3</sup> per annum there after. This scenario clearfall's an additional 2399 ha in the

first year than the scenario that provides for sustainable volume to 2026. The scenario that minimizes LAI without liquidated to waste in first year then 100000 m<sup>3</sup> per annum minimum until 2026 clearfall's an additional 625 ha than the scenario that provides for sustainable volume to 2026.

Table 16. Annual sustainable volume for scenarios in testing sensitivity to changing objective to minimizing LAI from maximizing sustainable volume

Annual sustainable volume (m <sup>3</sup> )	
Sustainable to 2026	123244
Minimize LAI with 100000 m <sup>3</sup> per annum minimum till 2026	120299

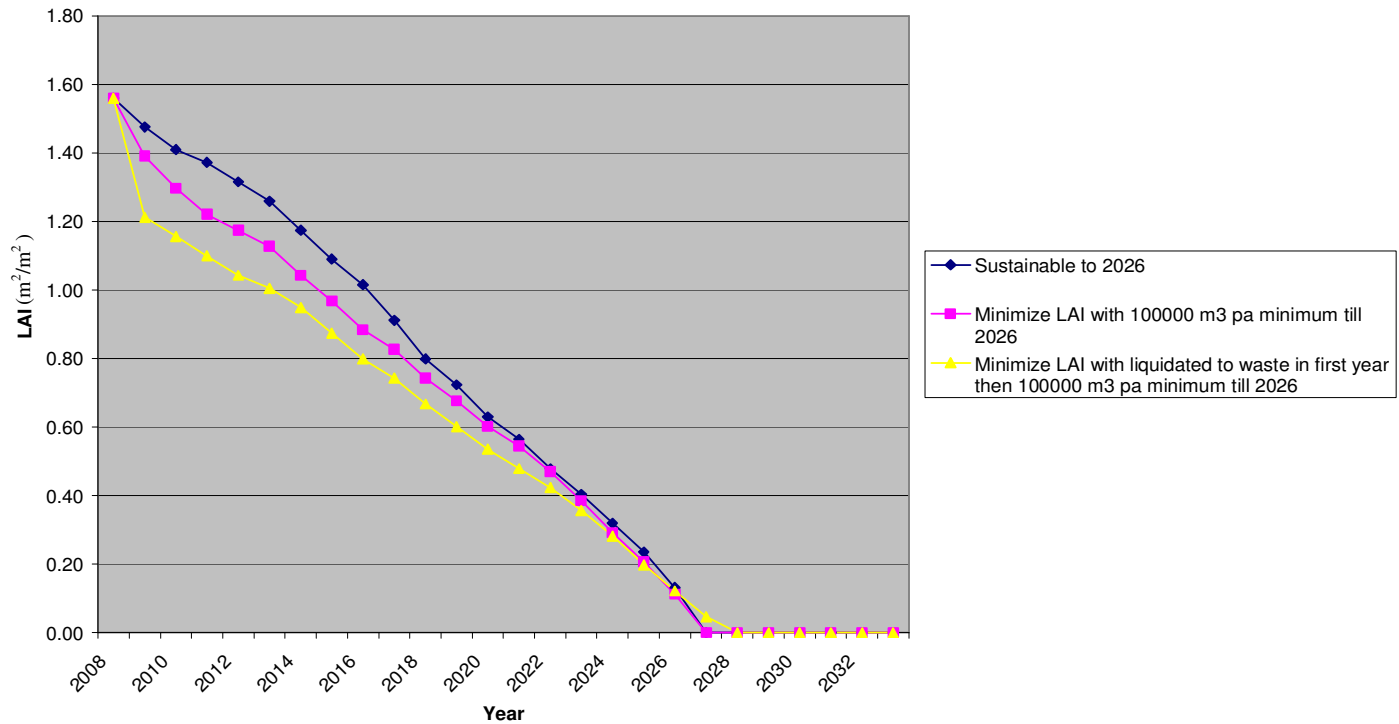


Figure 76. LAI outcomes for the scenarios Minimize LAI with 100000 m<sup>3</sup> per annum minimum till 2026, Minimize LAI with liquidated to waste in first year then 100000 m<sup>3</sup> per annum minimum till 2026 and Sustained to 2026 scenarios

There is a decrease of only 2945 m<sup>3</sup> per annum or 2.4% in annual volume between changing from optimising for maximum sustained volume and optimising to minimize LAI. With this decrease, the volume achieved from the LAI outcomes for Minimize LAI with 100000 m<sup>3</sup> per annum minimum till 2026 scenario still remains above the minimum supply 117000 m<sup>3</sup> per annum for the first 22 years to achieve the required contracted volumes. It is therefore feasible to choose to minimize LAI without lowering the volume outcomes significantly and avoiding compensation as contracted volumes can be achieved.

#### **x) Recharge outcomes**

The sustainable to 2026 scenario (which was the original scenario FPC had chosen to use) LAI outcome was converted to a recharge outcome using both the linear relationship developed in Figure 64 and the PRAMS LAI to recharge relationship from the classes of LAI in Table 6.

The results were an average of 45.5GL and 55 GL per annum respectively for the two recharge relationships. This amount assumes the area of *P. pinaster* Aiton once clearfallen will lay fallow and hence be similar to pasture in its recharge for such areas. A poorer recharge result will only occur if the areas once clearfallen are immediately regenerated to Banksia woodland. Experience from general observations by foresters over a number of years is that native revegetation on Gngangara Mound is very slow in regenerating naturally in areas that are clearfallen. Hence, it is proposed that a better comparison is that to one that is fallow for a period of time. It may however be an overestimate of recharge as some natural revegetation will occur but this is difficult to estimate.

An area of Banksia woodland at LAI 1 m<sup>2</sup>/m<sup>2</sup> that was equivalent to the size of that occupied by the pine, would recharge 39.4 GL using the linear relationship developed in Figure 64 and 36.2 GL if the PRAMS LAI to recharge relationship is used.

The LAI outcome for the sustainable to 2026 scenario is shown in Figure 77. The recharge percentage of rainfall for the sustainable to 2026 scenario is shown in Figure 78. Figure 78 shows that due to an increasing area of fallow after clearfall the recharge percentage of the sustainable to 2026 scenario exceeds that of Banksia at LAI 1 m<sup>2</sup>/m<sup>2</sup> after 2014 if the linear recharge to LAI hypothesis is used.

The LAI outcomes for Sustainable to 2026 were compared with the following scenarios:-

- Sustainable to 2016,
- Sustainable to 2021,
- Sustainable to 2029,
- 130000 m<sup>3</sup> per annum for first 5 years then even supply to 2026,
- 145000 m<sup>3</sup> for first 5 years then even supply to 2026,
- 160000 m<sup>3</sup> per annum for first 5 years then even supply to 2026,
- 175000 m<sup>3</sup> per annum for first 5 years then even supply to 2026,
- Minimize LAI with 100000 m<sup>3</sup> per annum minimum till 2026,
- Minimize LAI with liquidated to waste in first year then 100000 m<sup>3</sup> per annum minimum till 2026,
- 160000 m<sup>3</sup> for longest feasible time and Banksia at LAI 1 m<sup>2</sup>/m<sup>2</sup>.

The differences (Table 17 and Figure 79) were then converted to recharge outcomes differences using :-

1. The linear relationship developed in Figure 65 (Table 17 and Figure 78).
2. The PRAMS LAI to recharge relationship from the classes of LAI in Table 6. An example of LAI class outcome is shown in Figure 77

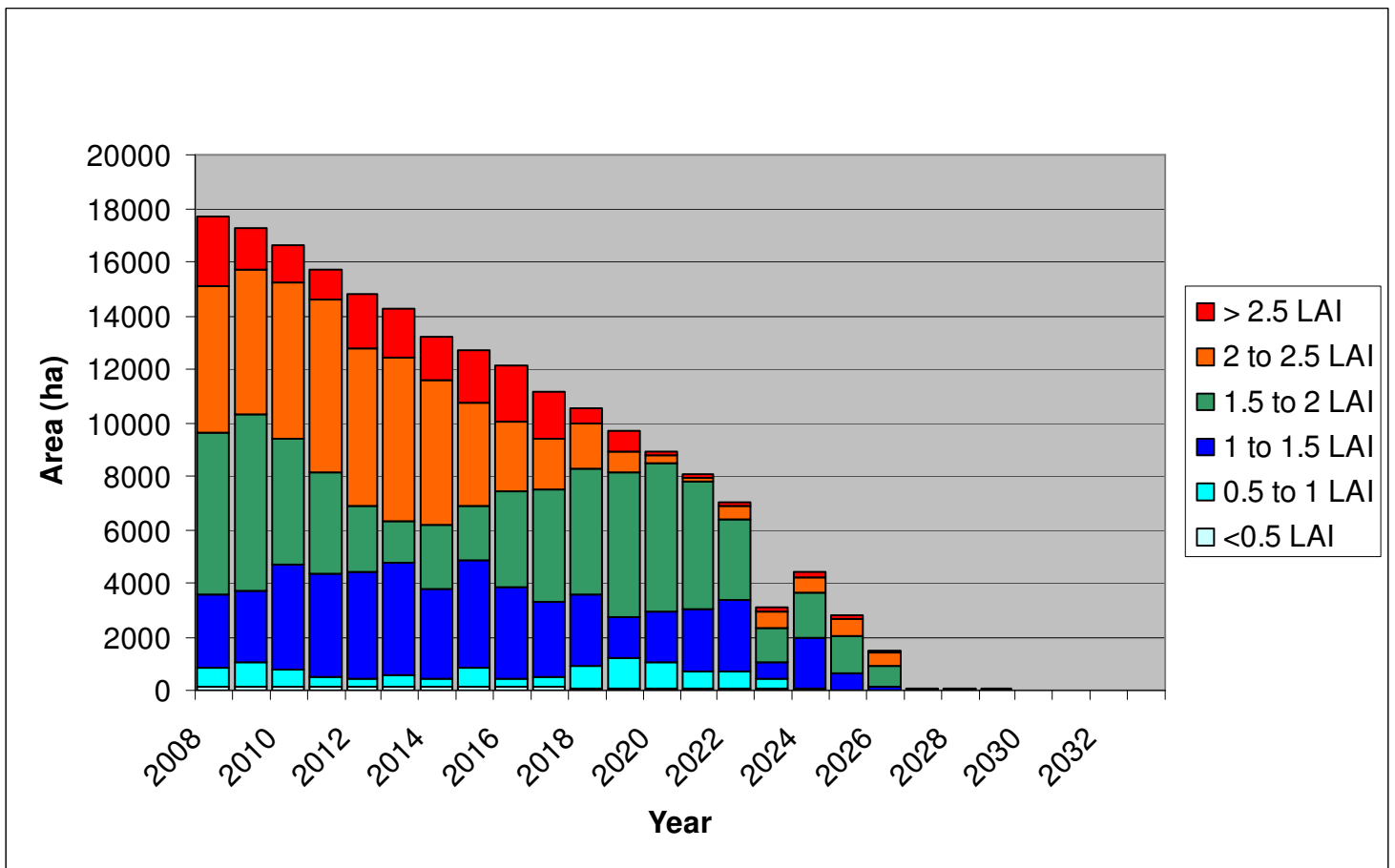


Figure 77. Standing pine LAI class outcome for Sustainable to 2026 scenario

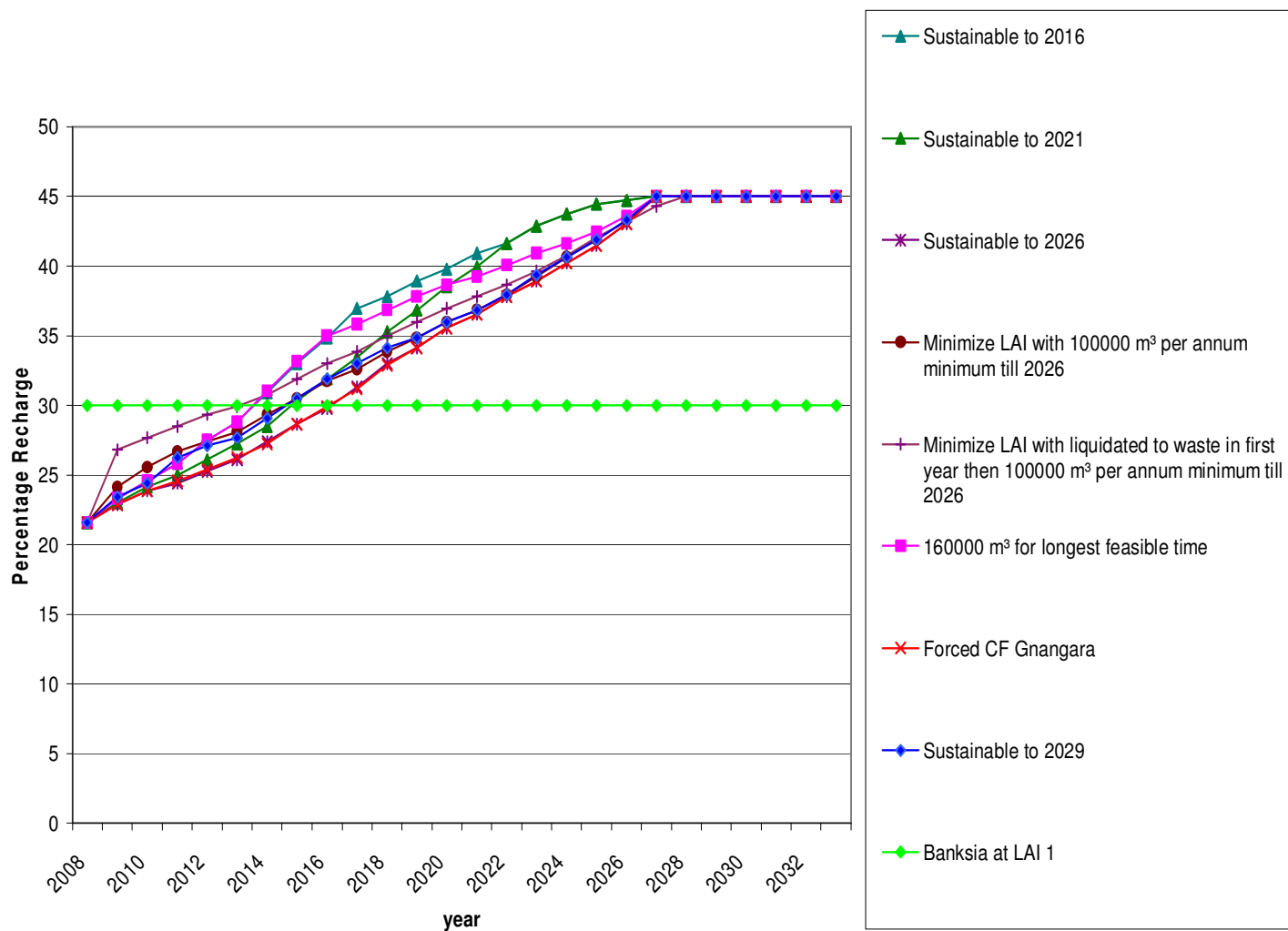


Figure 78. Comparison between scenarios for recharge using linear recharge to LAI hypothesis



Table 17. Scenario comparisons of water recharge outcomes to of the scenario that provides for sustainable volume to 2026

	Linear recharge to LAI hypothesis		PRAMS recharge to LAI relationship	
	Total Water 2008 to 2029 difference to Sustained supply to 2026 (GL)_	Average per annum water difference (GL/yr)	Total Water 2008 to 2029 difference to Sustained supply 2026(GL)	Average per annum water difference (GL/yr)
Sustainable to 2016	105	4.8	154	7.0
Sustainable to 2021	65	3.0	93	4.2
Sustainable to 2029	4	0.2	30	1.4
130000 m <sup>3</sup> per annum for first 5 years then even supply to 2026	35	1.6	26	1.2
145000 m <sup>3</sup> per annum for first 5 years then even supply to 2026	71	3.2	83	3.8
160000 m <sup>3</sup> per annum for first 5 years then even supply to 2026	8	0.4	15	0.7
175000 m <sup>3</sup> per annum for first 5 years then even supply to 2026	27	1.2	38	1.7
Minimize LAI with 100000 m <sup>3</sup> per annum minimum till 2026	46	2.1	71	3.2
Minimize LAI with liquidated to waste in first year then 100000 m <sup>3</sup> per annum minimum till 2026	80	3.6	120	5.4
160000 m <sup>3</sup> per annum for longest feasible time	67	3.1	94	4.3
Banksia at LAI 1	-134	-6.1	-414	-18.8

There is less recharge for Banksia because as previously discussed it is assumed the area of *P. pinaster* Aiton after clearfall will lay fallow and hence be similar to pasture in its recharge for such areas. There will be less recharge if the clearfallen areas are immediately regenerated to Banksia woodland. Experience from general observations by foresters over a number of years is that native revegetation on Gngangara Mound is very slow in regenerating naturally in areas that are clearfallen. Hence, it is proposed that a better comparison is that to one that is fallow for a period of time.

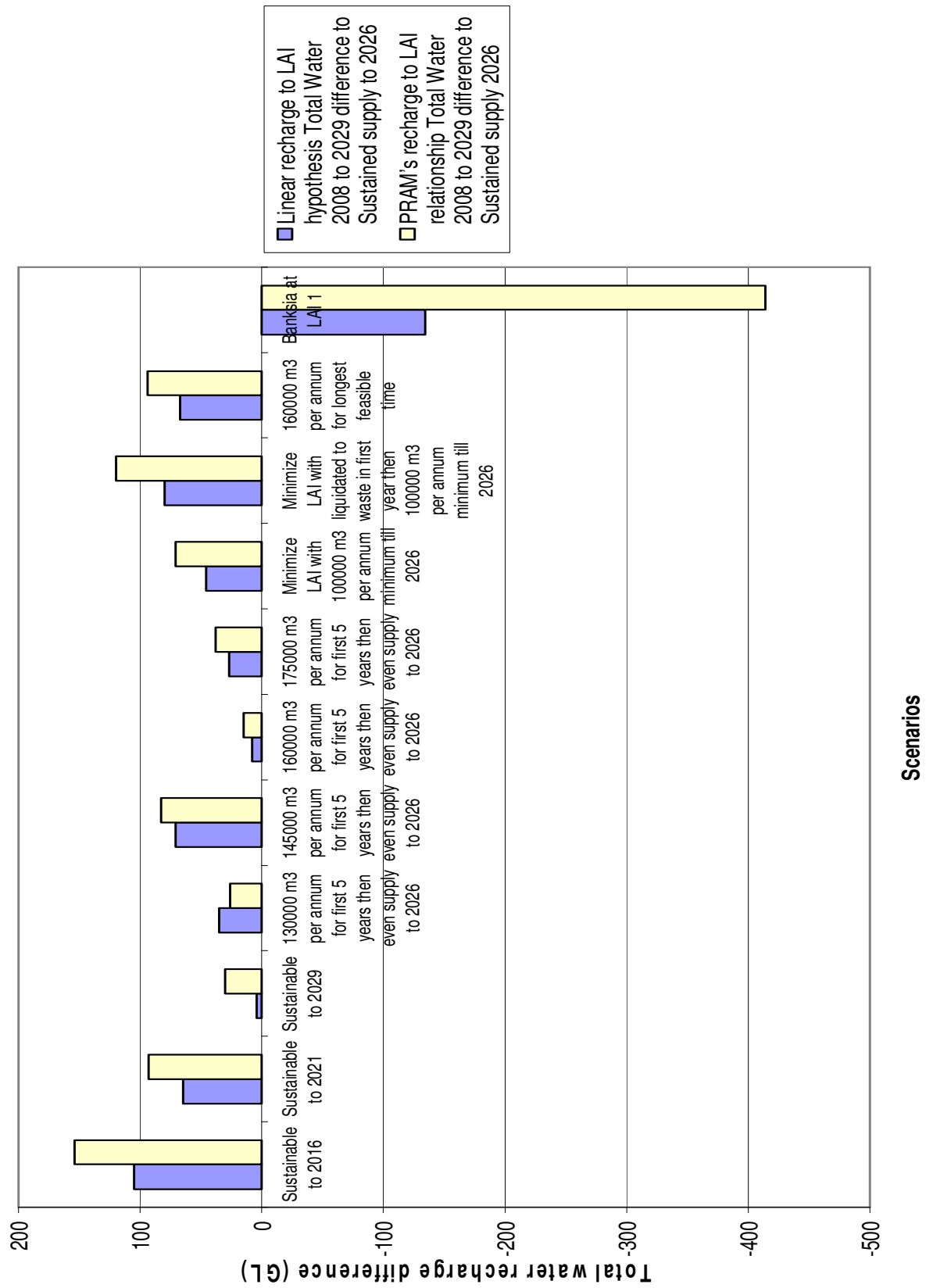


Figure 79. Scenario comparison of total water recharge to base sustained wood supply scenario

Liquidating the pine stands earlier does increase the recharge outcome. The majority of scenarios are in the same order of ranking for water outcome for both the linear recharge to LAI hypothesis and PRAMS recharge to LAI relationship. However, none of the differences in recharge between all of the scenarios is large.

When comparing the scenarios of Minimize LAI with 100000 m<sup>3</sup> per annum minimum till 2026 and Sustainable to 2026 there is only a small difference in volume as previously mentioned and the volume levels are still above the minimum supply of 117000 m<sup>3</sup> per annum for the first 22 years which is required to achieve the required contracted volumes set out in the Agreement Act. The corresponding difference in recharge between the scenarios is between 3.6 and 5.4 GL average per annum additional recharge.

#### **xi) Recommendations**

- Given the sensitivity to growth rates, it is recommended that FPC maintain a measurement program that tracks the achieved growth rates and if these are significantly different to those used in the normal growth rate scenario then the volumes available will need to be revised.
- Given the sensitivity to recovery rates of LVL it is recommended that FPC tracks the achieved recovery rates and measures stands just prior to harvest and if these are significantly different to 70% then the volumes available will need to be revised. To date there has only been limited reliable data available on recovery rates that can be used to predict future recoveries.
- Targeting Gngangara for clearfall earlier than Pinjar and Yanchep has little impact on volumes achieved and would improve the time to recharge the

groundwater tables as these are shallower in Gngangara and the infiltration down to the water table would be significantly faster because of the short distance below the surface to the water table and hence less total water required to cause leakage from the profile above the water table. Therefore then a strategy that includes forcing Gngangara plantation to be liquidated in 5 years is recommended.

Scenarios that attempt to achieve an early liquidation result in only a small gain of water for a larger loss of volume and this results in volumes lower than is contracted for and therefore may require a consideration of a compensation figure that may be greater than the value of the water yielded. There is also a significant risk that sufficient rainfall to achieve these recharge outcomes is not forthcoming. A loss of 100mm rainfall per annum across the entire Gngangara Mound, assuming a potential recharge of 45%, is equivalent to a loss of 107 GL per annum. Even at the maximum annual average gain of 5 to 7 GL per annum from early liquidation this is only equivalent to only 4 to 6.5mm less rainfall across the entire Gngangara Mound using the same assumptions. There is a risk that climate variability will continue and it only requires a small future rainfall reduction to remove any gains in water yield. It is therefore recommended not to use strategies that would achieve an early liquidation because the gains for water are not sufficiently large to warrant them.

However, even within a tightly constrained case study like the *P. pinaster* Aiton on Gngangara Mound there are worthwhile gains that can be made in water recharge if the harvesting is driven by LAI minimisation within acceptable volume outcomes.

## **8. Other factors affecting the Gnangara Mound groundwater system**

### **i) Introduction**

There are other factors affecting the groundwater system beyond thinning and harvesting of *P. pinaster* Aiton on the Gnangara Mound. Climate, abstraction of water and fire regimes are the other main factors (Response to Peer Review Panel Comments 2002).

Live plant biomass uses water in its life processes and dead biomass such as needle beds or litter layers intercepts and re evaporates water (Seitz and Escobedo 2008). Managing only one component of the biomass may lead to having gains won being lost through replacement by another component. For example thinning of pines will lead to a more open canopy and may lead to a more luxurious scrub layer below that then uses all the water gained through thinning.

Comprehensive management of the whole biomass would therefore require management of needle bed levels and scrub under the pine plantation and fuel ages in the native vegetation as well as pine tree density. There are also other options for management of *Pinus pinaster* Aiton beyond thinning that could be used to increase recharge.

### **ii) Other options for management of *Pinus pinaster* Aiton beyond thinning to increase recharge**

#### **a) Pruning**

Pruning would reduce LAI (at a cost), it would also increase quality of LVL by reducing limb size in area pruned on trunk and it would also aid in fire control.

At the time of pruning at age 10, approximately one third of the leaf area of a tree would be removed. This could be significant in younger stands for water recharge. Most of the plantation has been pruned. The practice however was stopped in the early 1980's when the cost of pruning became uneconomic for timber production. Only the last of the young plantations planted after 1984, which are mostly in Yanchep plantation were not pruned. This is an area of approximately 2500ha. If the PRAMS water recharge to LAI relationship is used then this would not increase recharge. If however, the hypothesised linear LAI relationship to water recharge is used a total increase of 9.2 GL would occur over the period until 2026.

b) Underpine burning

Underpine burning to remove and reduce the needle bed below the *P. pinaster* Aiton canopy would increase water recharge by allowing more recharge to penetrate the soil rather than being held up and re-evaporated from a thick needle bed. Most of the pine is already regularly underpine burnt. An estimate of how much additional recharge with increased underpine burning is beyond the scope of this study.

c) Underpine scrub control

Underpine scrub reduction would lead to an increase in recharge or at least no additional loss if regrowth were controlled. Gains in recharge from pine thinning could be lost with an increase in scrub underneath the pines.

**iii) Management options for non pine components of the Gngangara Mound**

a) Native vegetation

The management regime used for native bush areas of the Gngangara Mound will contribute to assisting in the management of a portion of the Gngangara Mound's biomass. An important factor that will need to be considered is what condition is the native bush area of Gngangara

Mound . Particularly the factors such as fuel age and weight are important. How these may impact on groundwater recharge should be determined.

There is evidence of recharge after fire from hydrographs reported upon by Yesertener (2002) (Figure 80). PM5 site was subject to a large bushfire but Lake Pinjar site was not in both 1990 and 1994. This provides an estimate of the impact of shrub and litter removal on recharge.

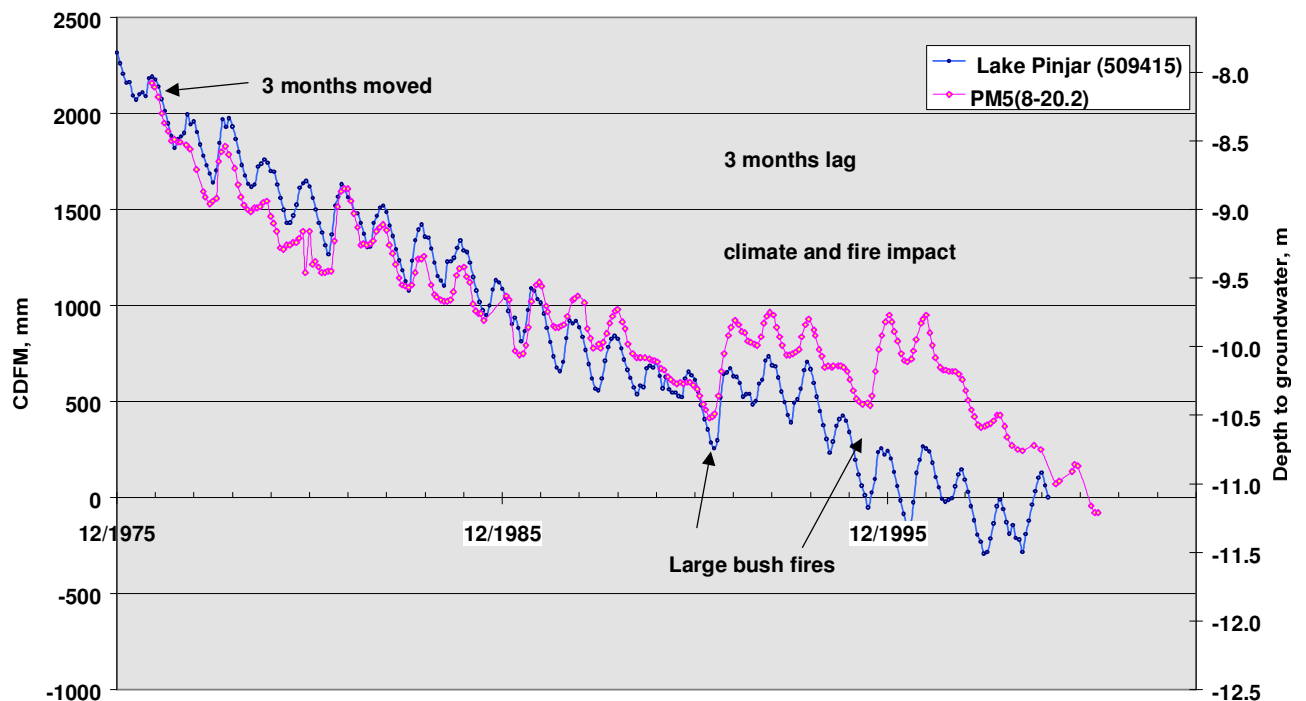


Figure 80. Example of fire effects on native woodland - from Yesertener, C., 2002, Declining water levels in the Gnangara and Jandakot Mounds (Stage 1), Hydrogeology Report HR199, Department of Environment. Used with permission

#### b) Native Vegetation and Fire

Farrington et. al. (1989) suggests that regular reduction in vegetation by controlled burning would increase recharge. Also evidence from Figure 80 above shows an improvement in water recharge after fire. Fire frequency in the bushland to the east of the pine plantations at

Gnangara Mound declined as can be seen from area circled in red in Figure 81. There appears to be an equivalent reduction of one autumn burn per decade. It therefore follows that recharge from these events is occurring less frequently and this has possible consequences in reducing the average annual recharge. The area of the Gnangara Mound that is native vegetation is approx 67000ha.

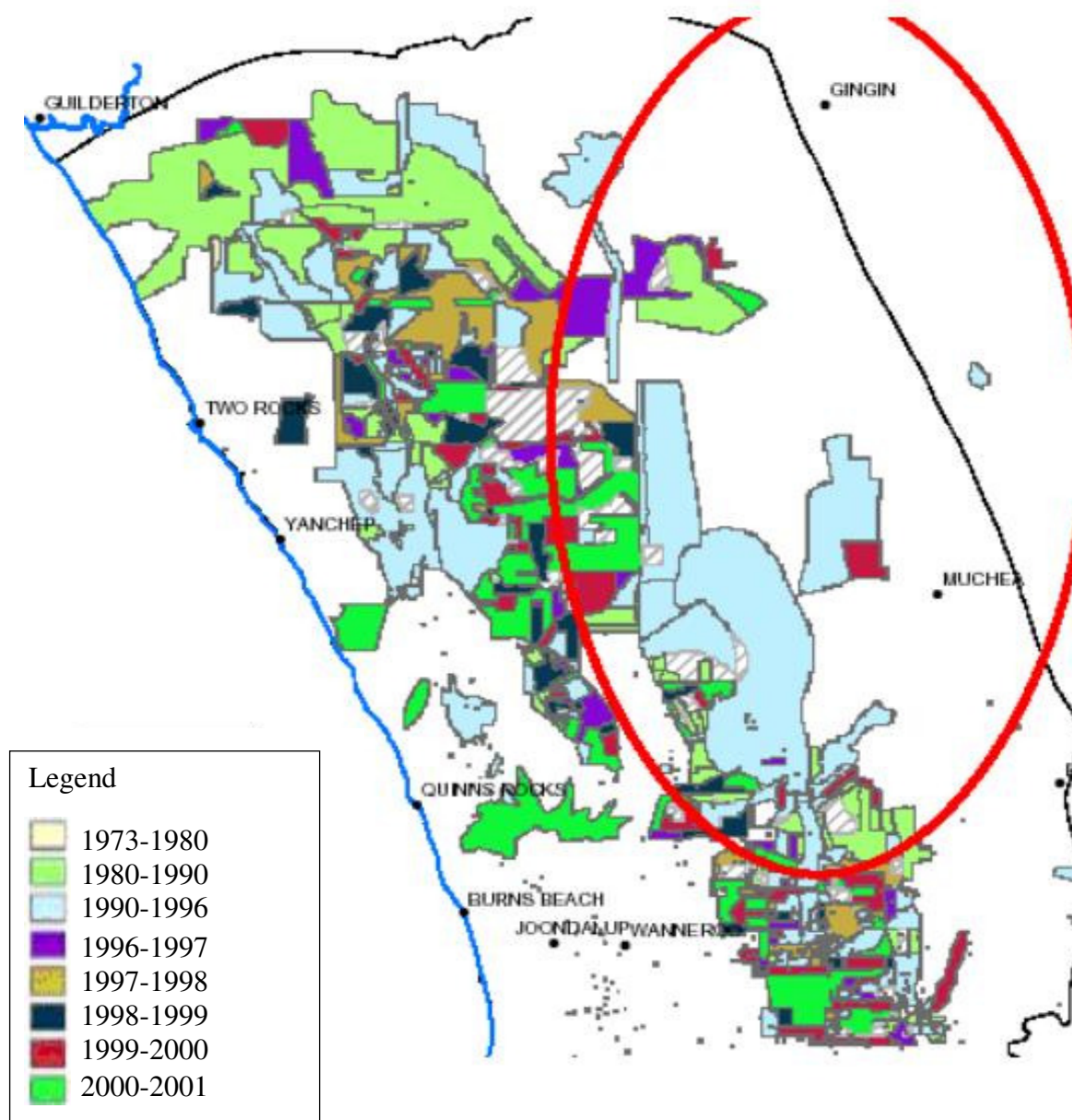


Figure 81. Last prescribed burn or wildfire (information supplied by DEC 2002)



The following analysis was reported by the author in Department of Environment (2005).

If Farrington et. al. (1989) is correct that the additional recharge after a fire in native vegetation will increase by approx 25% in the first year after the fire. The Banksia woodland then over time regenerates back to previous LAI's and again utilizes pre fire water amounts. From the authors personal observations it appears to regenerate after fire back to previous LAI's quickly. For the calculations below then it has been assumed that it will then return to pre fire levels over a short period of 4 years . If you assumed that after a fire event additional recharge occurs as follows:-

Year 1	25% extra recharge
Year 2	18.75% extra recharge
Year 3	12.5% extra recharge
Year 4	6.25% extra recharge
Year 5 to year 10	0% extra recharge

This data suggests that on average an additional recharge of 6.25% over a decade would occur if the area was burnt on a 10 rotation.

That is assuming average rainfall of 800 mm per annum rainfall then 50 mm additional recharge per annum would occur.

If fire frequency has been reduced by one autumn fire per decade over the 67000 ha of native vegetation on the Gngangara then there would be a 33.5 GL per annum recharge loss.

This level of recharge loss is a similar order of magnitude to that calculated using PRAMS modelling for the pines decreasing recharge on Gngangara mound before 2002.

If the PRAMS model calibration does not consider burning effects then it could be over prescribing other land use impacts of abstraction and Pine plantations as it uses the decline in

water tables as a method of calibrating PRAMS and it would be attributing all decline to factors other than burning.

Vogwill, McHugh, O'Boy and Yu (2008) state that “changing native vegetation density by increasing the annual percentage area of burning is an effective method for increasing recharge, particularly in the northeast part of the Gngangara Groundwater Mound (i.e. Yeal Swamp)” (p. 60). Vogwill, McHugh, O'Boy and Yu (2008) state that “large areas of the mound have not been burnt for at least 10 years with some areas up to 25 years” (p. 65). Vogwill, McHugh, O'Boy and Yu (2008) conclude that the “burning regime over the last 25 years has reduced recharge” and this has “contributed to additional water table decline” (p. 66).

#### c) Climate

As discussed and presented in Chapter 1 (Figure 3 p. 27 ) rainfall has declined since 1969.

The period between 1914 and 1969 is recognized as much wetter than the period from 1970 and 2007. The reduction of rainfall on average is approximately 100 mm less per year.

The rainfall has reduced since 1970 and there is a more recent reduction in climate wetness index (rainfall divided by pan evaporation) as shown in Figure 82. Given both these factors, the water tables at Gngangara Mound would naturally be expected to become lower than those prior to 1970.

An annual rainfall of 100mm less per annum equates to an approximate reduction from 800 mm at Wanneroo to now 700mm per annum. This 100 mm reduction across the entire Gngangara Mound results in a very large reduction in potential recharge. Assuming 45% of rainfall would have been available to recharge approx 107 GL per annum reduction in recharge could be attributed to rainfall reduction. This reduction is far greater than that amount reported from PRAMS modelling of the effect of pine plantations on recharge to be

used by the plantation. The change in climate since the early 1970s is the largest factor impacting on the water table levels on the Gngangara Mound.

Vogwill, McHugh, O'Boy and Yu (2008) observations that "PRAMS modelling demonstrates that regionally climate is an important input component ...and that climate change is one of the main drivers of groundwater declines on Gngangara Groundwater Mound" (p. 64).

Vogwill, McHugh, O'Boy and Yu (2008) further state "the results predict that the watertable will continue to decline over large areas... if all other components are held constant" (p. 64).

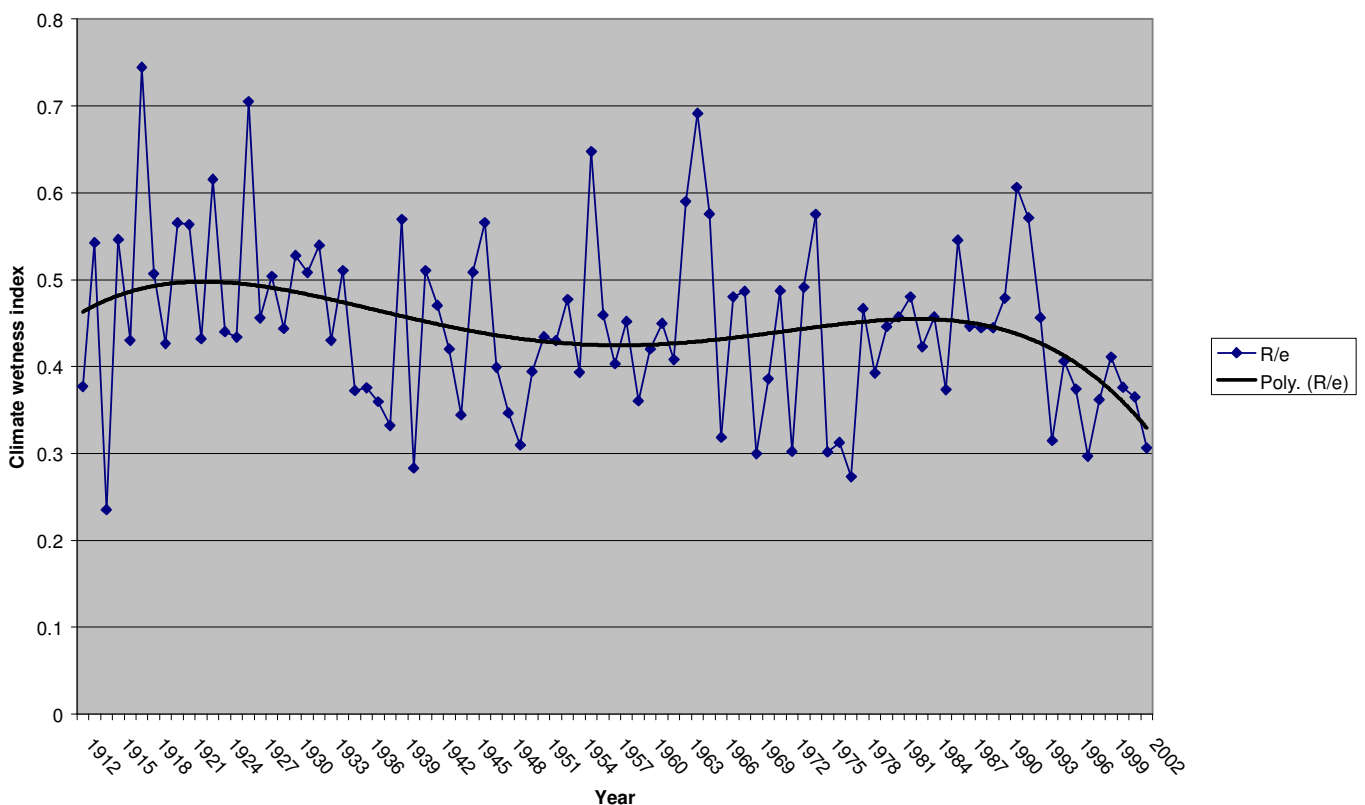


Figure 82. Climate wetness index for Perth (Rainfall and pan evaporation figures as obtained from Bureau of Meteorology)

#### d) Water abstraction

Department of Water (2008) sets out the new allocation targets water usage on the Gngangara Mound. Department of Water (2008) proposes that this allocation will be above the acceptable limit in more than half of the areas it will be drawn from. The expected water

abstraction for both private and public water usage is proposed by the draft management plan to be 304GL per annum. Given the former mentioned over allocation it then appears that water abstraction is going to be allowed to continue to be unsustainable. The abstraction level even at this reduced rate is in excess of 10 times that thought to be used in the late 1990's and early 2000's by the pine plantations. It would then seem logical to put the most management effort in the area of largest water usage rather than into one of the smaller usages such as pines. Particularly, as this usage is reducing with the staged removal of the pines.

## 9. Outcomes of the study

### i) Relevance of the techniques and experience gained to other problems elsewhere

One of the key messages of the Australian Water Review in 2005 was that “Australia is on balance a very dry continent and water resources are scarce in many areas” and “striking an appropriate balance between the consumptive use of the resource and the health of rivers and wetlands is a key element of the National Water Initiative” (AWR 2005 p. 6). Water availability has become a major issue in Australia over the last decade with successive droughts in southern Australia. Plantation water use like every other water use has and will remain an area of debate.

Much of the data used in this study to assess the options for silviculture and the subsequent water outcomes at other sites are available.

Landsat scenes are available every 16 days from 1987 onwards and can be obtained from archived collections (Landmonitor 2006). Once a portion of a plantation set has reached canopy closure, the site maximum LAI for the species can be determined. This could be derived from experimental plantings or Arboreta as long as the plot size is equal to or greater than one of the pixels on the Landsat scene. For the Landsat used at Gngangara Mound this pixel size was 25 metres by 25 metres, which is relatively small. Calibrating the satellite photography from ground truth samples is relatively simple following the techniques developed by CSIRO (Hodgson 2003). Although regrowth of LAI following thinning does appear to reduce with increasing age of stands this should not be a great issue in most pine or eucalypt rotations in Australia as these are normally grown on relatively short rotations of less than 40 years. It would be possible to ignore this decline of rebound and still obtain a reasonable prediction of LAI outcomes in a silvicultural regime that has thinnings. In a clearfall without thinning silvicultural regime this would not be an issue. Determining the time to reach canopy closure from planting would be the only variable, which would have to be determined in this case. When a LAI prediction for the life of a plantation area has then

been derived a recharge or runoff relationship to LAI can then be added. It would then be possible to predict future water recharge yield outcomes.

If water yields from an area of plantations become a significant issue in an area then others in that situation should then consider repeating using the approach used in this in this study of the *P. pinaster* Aiton on the Gngangara Mound. This study has shown that robust models need to be developed to describe the water use across a plantation estate that has varying silviculture over time and space. Without them, a lack of scientific rigor will result in poor decision making.

The results from this case study show that it is possible and worthwhile to drive the choice of silvicultural regime of a plantation estate using an objective which seeks to minimize LAI and hence maximize water recharge even within very tightly constrained volume requirements. Measurement and understanding LAI outcomes can be carried out using remote sensing from satellite photography.

It should even be possible to estimate a proposed plantations water usage outcome prior to establishment. This would require reasonable judgements for a particular site as of time to canopy closure, maximum LAI achieved and desired silvicultural regime and its impacts on LAI growth to be made.

## **ii) Summary of the recommendations for harvesting regimes to maximise groundwater recharge on Gngangara Mound**

There is already a substantial gain by choosing to liquidate the *P. pinaster* Aiton on the Gngangara Mound by following the harvesting regime within the scenario Sustainable volumes to 2026 (Table 18). Within the constraints of the State Agreement Act there is an additional small gain of 2 to 3 GL per annum that can be made by choosing to drive the harvesting schedule with an objective that seeks to minimize LAI provided the volumes from 2008 to 2026 are no lower than 117000 m<sup>3</sup> per annum. The scenario that seeks to Minimize LAI with

a constraint of minimum volumes of 100000 m<sup>3</sup> per annum until 2026 achieves this as it chose to cut 120000 m<sup>3</sup> per annum due to other constraints in the model.

It is also possible to combine this with a goal of seeking to maximize the forced liquidation of Gngangara plantation rather than Pinjar and Yanchep within the next 5 years (which could be achieved without substantial loss of volume) and still meet the minimum 117000 m<sup>3</sup> per annum volume. This would result in the best water outcome within the constraints because the shallower depth to ground water in Gngangara would allow for the quickest recharge. Again, the additional small gain is only 2 to 3GL per annum when compared to the scenario with sustainable volumes to 2026.

Any scenario that can be made by choosing to drive the harvesting schedule with an objective that seeks to minimize LAI provided the volumes from 2008 to 2026 that are no lower than 117000 m<sup>3</sup> per annum combined with a forced liquidation of Gngangara plantation rather than Pinjar and Yanchep within the next 5 years will achieve the best water outcome within the constraints of volume.

Anything that shortens the time of liquidation of the plantation will increase the water recharge but the water outcomes are small in comparison to the volume loss. The additional water gained through the revoking of the State Agreement Act constraints by harvesting to achieve an early liquidation is relatively small compared to the costs that would be incurred in compensation. A saving of between 5 and 7GL per annum could be found for a much lower cost by focusing on some other water saving mechanism such as *Banksia* water use control using prescribed burning or less water extraction for private use. The small gain resulting from reducing timber yield would be insignificant compared to the loss resulting from a small reduction in annual rainfall.

Table 18 Harvesting scenario and other options comparison (where a range is show First figure assumes linear recharge to LAI hypothesis and second figure the PRAMS recharge to LAI relationship)

Management Scenarios	Average per annum increase in water recharge (GL)
Prescribed burning native vegetation	33.5
A reduction of private and public abstraction from 370 to 304GL/yr	66
Harvesting regime for Sustainable timber volume supply to 2026	45.5 to 55
Harvesting regime for Minimize LAI with 100000 m <sup>3</sup> timber volume supply per annum minimum till 2026	47.6 to 58.2
Harvesting regime for Sustainable timber volume supply to 2016	50.5 to 62

An equivalent area of pine as Banksia at LAI 1 m<sup>2</sup>/m<sup>2</sup> would recharge annually 39.4 to 36.2

GL. A continuing lower rainfall of 100mm less than long term average would mean a ongoing reduction of recharge annually of 107 GL to that achieved prior to 1970.



## **Ethical statement**

Forest Products Commission has requested that commercial information not be divulged. CSIRO and DEC have requested that unpublished research be duly acknowledged. These requests were complied with. Where information from other concurrent studies was used, it was appropriately acknowledged.

## **Acknowledgements**

I am grateful for the sponsorship by Forest Products Commission (FPC) through a generous scholarship. I am extremely grateful for the patience and wisdom provided by my supervisors Dr Syd Shea and Dr Lou Caccetta.

I am also grateful for the invaluable assistance from the other members of the Gngangara technical groups particularly Mr Robert Stokes formerly of Water Corporation, Michael Martin Water Corporation and Mike Canci Water Corporation. Without their considerable ongoing efforts in discussing and investigating aspects of both the science and practical solutions, the task of tackling the issues would be considerably more difficult.

I would like to also acknowledge the assistance provided by both Dr Stephen Hill and Mark Grigoleit and from Curtin University with the parameterisation of the optimisation.

I would finally like to acknowledge Mr Eric Hopkins retired, Mr Trevor Butcher FPC, Dr Peter Ritson FPC, Dr John McGrath FPC and Ian Dumbrell FPC for their generous access to some of their unpublished studies and data.

## Appendix 1

### Total Laminated Veneer Lumber supply

Operation year	Volume	Minimum <i>P. pinaster</i>	Maximum <i>P. radiata</i>	Maximum average haul	Minimum average age <i>P. pinaster</i>	Minimum average age <i>P. radiata</i>
2003/4	120000	96000	24000	50	40	30
2004/5	120000	96000	24000	50	40	30
2005/6	120000	96000	24000	50	40	30
2006/7	120000	96000	24000	50	40	30
2007/8	120000	96000	24000	50	40	30
2008/9	120000	96000	24000	50	40	30
2009/10	160000	128000	32000	75	40	30
2010/11	160000	128000	32000	75	40	30
2011/12	160000	128000	32000	75	40	30
2012/13	160000	128000	32000	75	40	30
2013/14	160000	128000	32000	75	40	30
2014/15	170000	136000	34000	68	40	30
2015/16	170000	136000	34000	68	40	30
2016/17	170000	136000	34000	68	40	30
2017/18	170000	136000	34000	68	40	30
2018/19	170000	136000	34000	68	40	30
2019/20	175000	140000	35000	83	40	30
2020/21	175000	140000	35000	83	40	30
2021/22	175000	140000	35000	83	40	30
2022/23	175000	140000	35000	83	40	30
2023/24	175000	140000	35000	83	40	30
2024/25	175000	140000	35000	106	35	30
2025/26	175000	140000	35000	106	35	30
2026/27	175000	140000	35000	106	35	30
2027/28	175000	140000	35000	106	35	30
2028/29	175000	140000	35000	106	35	30
Total	4120000	3296000	824000			

Minimum age 25 years old

Minimum economic volume for thinning 40 cum /ha

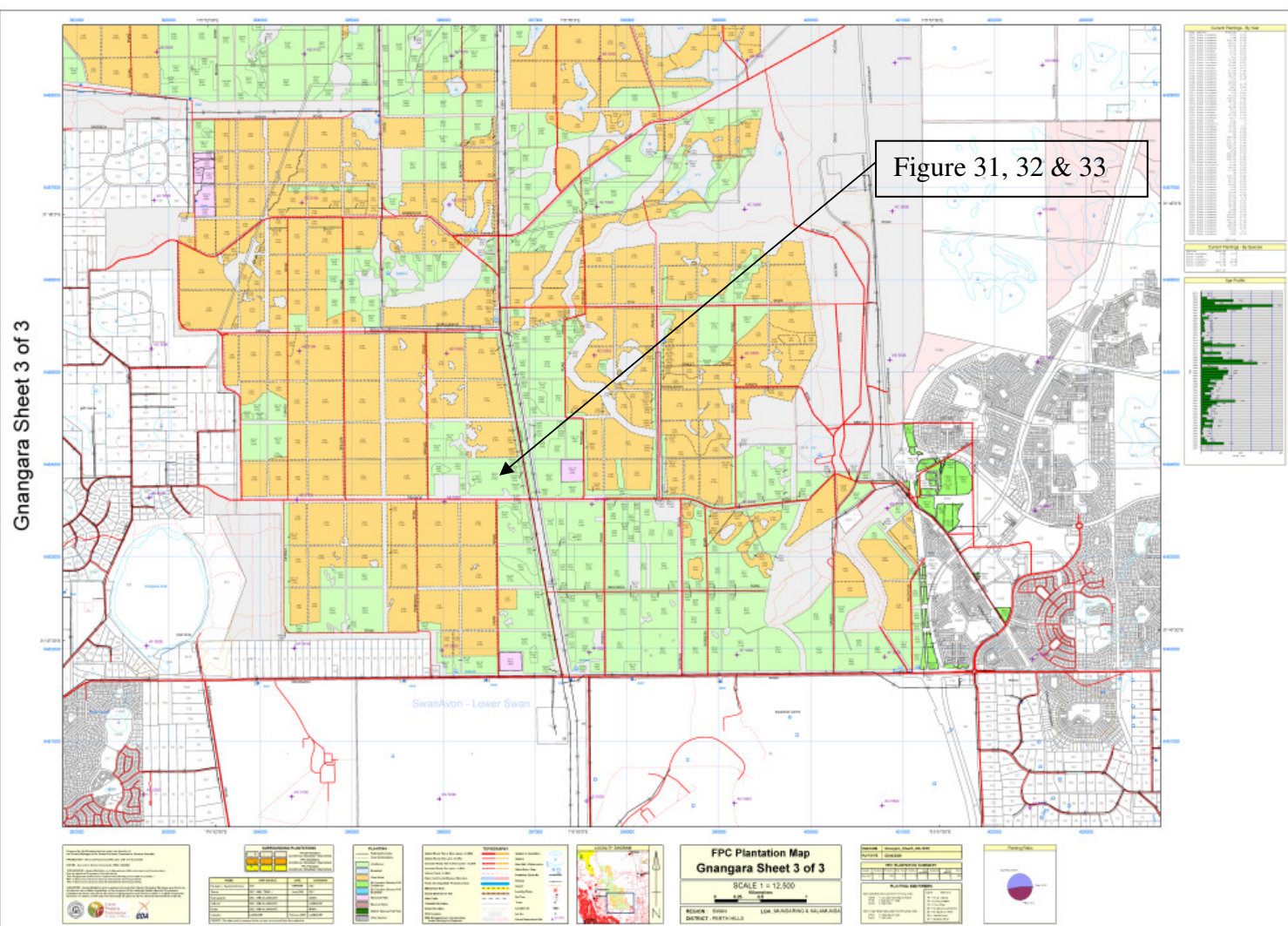


Figure 83 Gngara plantation map sheet 3 of 3

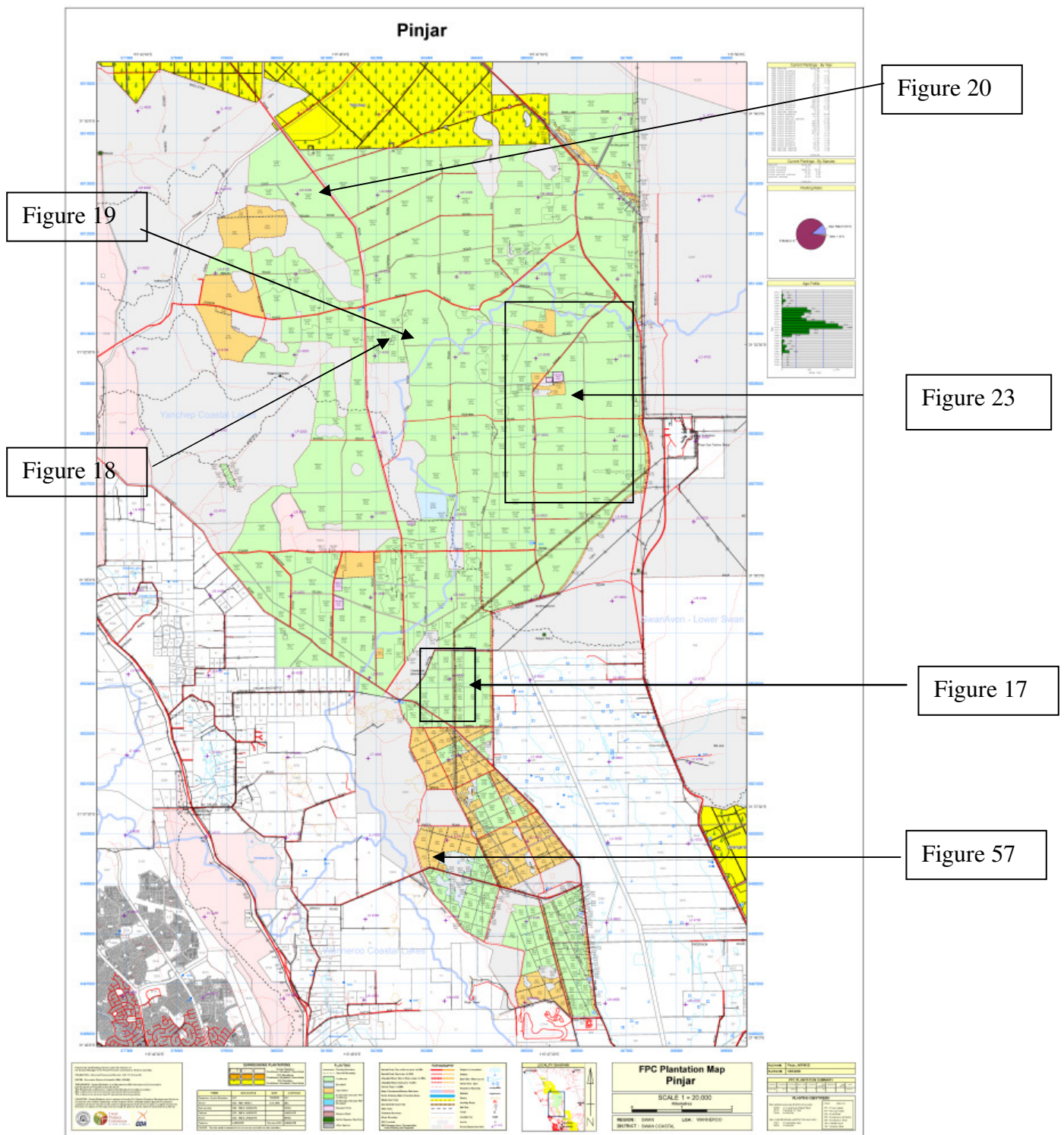


Figure 84 Pinjar plantation map



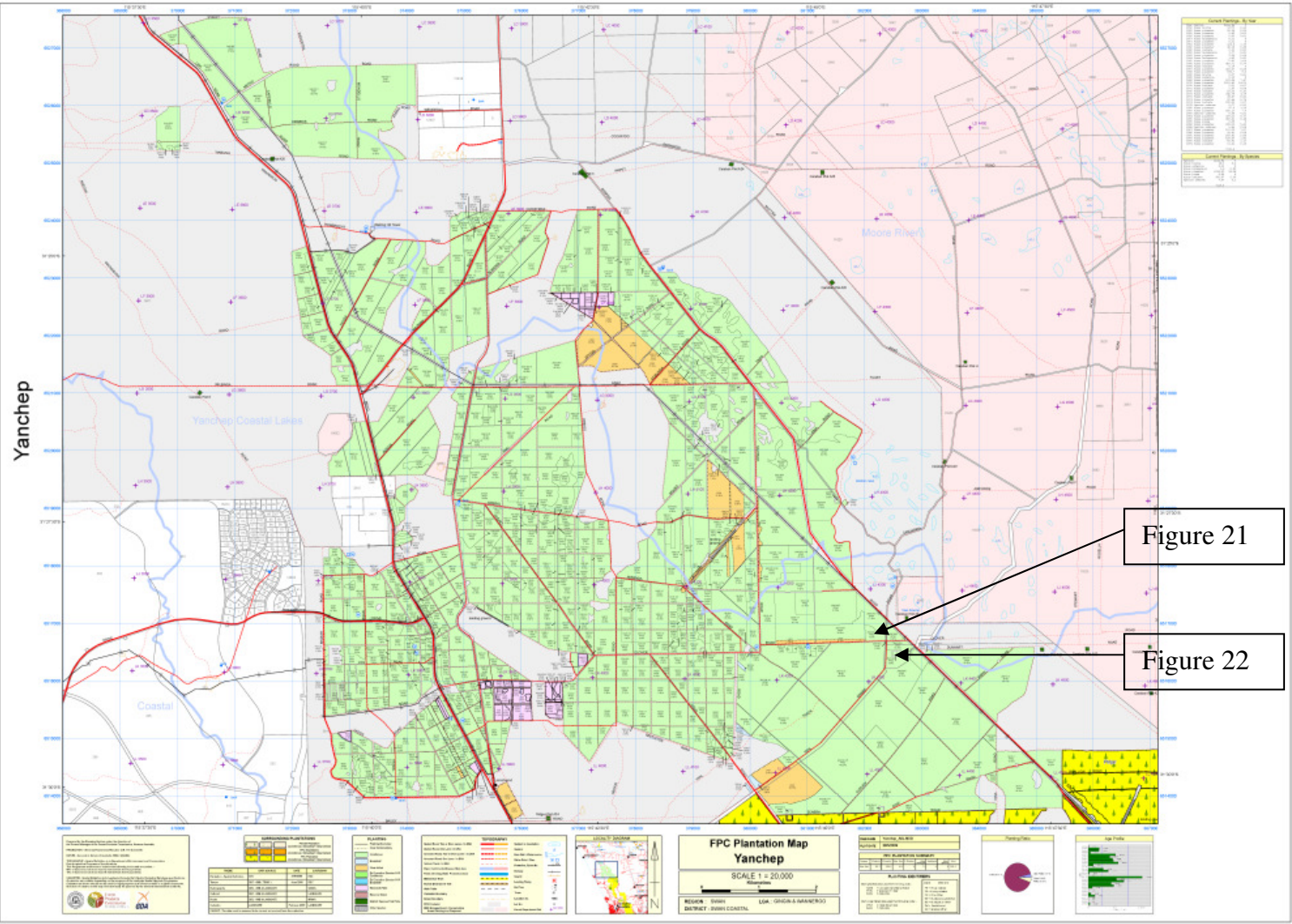


Figure 85 Yanchep plantation map

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